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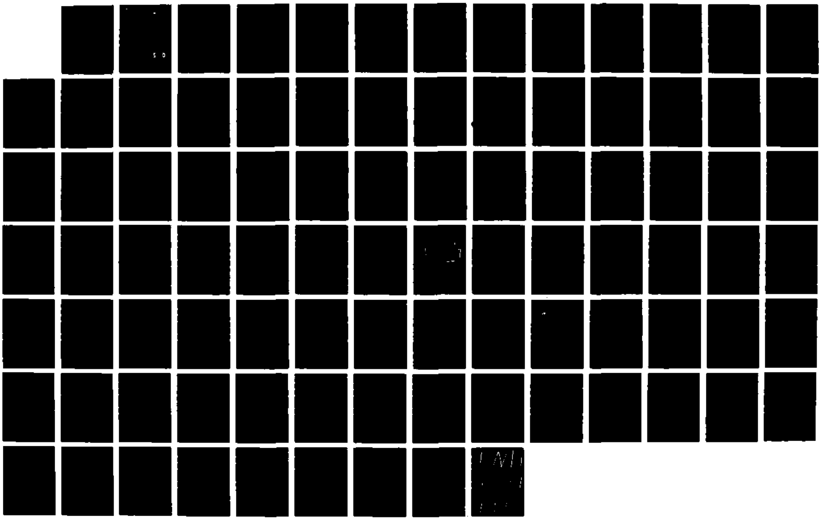

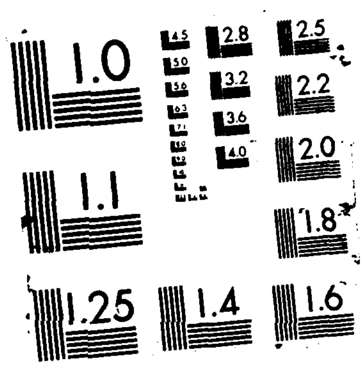
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US Army Corps of Engineers
Construction Engineering Research Laboratory

USA-CERL TECHNICAL REPORT N-87/27
September 1987

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An Evaluation of the MULTSED Simulation Model to Predict Sediment Yield

by
Harry G. Wenzel, Jr.
Charles S. Melching

The MULTSED (Multiple Watershed Storm Water and Sediment Runoff Simulation) model was evaluated as a tool which will help Army land managers assess the environmental conditions of troop training areas to determine the need for remedial action. The sensitivity of model parameters was explored using two watersheds. Guidelines for calibrating the model were developed based on a "best fit" criterion between measured and computed runoff hydrographs. The results support MULTSED application and indicate how improvements to the model can be made.

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FOREWORD

This work was conducted for the Office of the Chief of Engineers (OCE) under Project 4A162720A896, "Environmental Quality Technology"; Technical Area A; "Installation Environmental Management"; Work Unit 041, "Training Management and Geographic Decision Support System." The OCE Technical Monitor was Donald Bandel, DAEN-ZCF-B.

This evaluation was completed by Harry G. Wenzel, Jr. and Charles S. Melching of the Department of Civil Engineering, University of Illinois, Urbana-Champaign for the Environmental (EN) Division of the U.S. Army Construction Engineering Research Laboratory (USA-CERL). The authors are indebted to Mr. John Gray, U.S. Geological Survey, Urbana, Illinois, for providing preliminary data and assistance with the Sheffield site used in the calibration study. Mr. Robert E. Riggins was USA-CERL's principal Investigator. Dr. Ravinder K. Jain is Chief of USA-CERL-EN. The Technical Editor was Gloria J. Wienke, Information Management Office.

COL Norman C. Hintz is Commander and Director of USA-CERL, and Dr. L. R. Shaffer is Technical Director.

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AN EVALUATION OF THE MULTSED SIMULATION MODEL TO PREDICT SEDIMENT YIELD

1 INTRODUCTION

Background

Army installations must continue using troop training lands, while at the same time protecting the environment. Maintenance of Army training lands is important because the acquisition of new lands is difficult and because current training practices use the lands more intensively than in the past.

As an integral part of the land management technology being developed, the U.S. Army Construction Engineering Research Laboratory (USA-CERL) has undertaken a research project aimed at maintaining the environmental quality of the U.S. troop training areas. One aspect of this project is to identify and implement methods which will help land managers decide when environmental conditions of training lands have declined to the point where remedial action is needed.

Although training activities affect many environmental quality parameters (e.g., biological or chemical), the most sensitive parameter is vegetal cover. Destroying vegetal cover increases the magnitude of the erosion-deposition process and the resulting sediment yield. A mathematical computer model which predicts sediment yield and relates training activities to changes in model parameters can be useful for evaluating activities and practices. Such a model should reflect the variables which control sediment yield including soil type, vegetal cover, and hydrological factors.

For the purpose of this study, it was desired to identify a single event model which could simulate sheet and channel erosion, splash detachment, and compute sediment yield in addition to the runoff hydrograph. Furthermore, the model should have the ability to reflect the effect of various proposed erosion control management procedures. Of the number of erosion and/or sediment yield models available, the Multiple Watershed Storm Water and Sediment Runoff Simulation (MULTSED) Model most closely meets these criteria. MULTSED was developed at Colorado State University by Simons et al.[1] under the sponsorship of the U.S. Department of Agriculture (USDA) Forest Service.

Objectives

The objectives of this research were:

1. To explore and evaluate the MULTSED model, including the sensitivity of model parameters

2. To develop a procedure and guidelines for calibrating the model

[1] D. B. Simons, R. M. Li, and B. E. Spronk, *Storm Water and Sediment Runoff Simulation for a System of Multiple Watershed—Vol I, Water Routing and Yield*, CER77-78DBS-RML-BES47 (Colorado State University, April 1978); D. B. Simons, R. M. Li, W. T. Fullerton, and T. R. Grindeland, *Storm Water and Sediment Runoff Simulation for a System of Multiple Watersheds—Vol II, Sediment Routing and Yield* (Colorado State University, October 1981).

3. To investigate and identify a specified rainfall event or "design storm," which could serve as a standard for the planning and evaluation process.

Approach

An initial evaluation of the MULTSED model was done using two watersheds. The response of the model was documented in terms of peak outflow and sediment yield response to variations in rainfall depth, duration, and temporal distribution. The effect of soil and land use parameters was also studied.

A formal calibration procedure was developed to evaluate the hydrologic parameters of the model. This was based on a "best fit" criterion between measured and computed runoff hydrographs using the generalized reduced gradient (GRG) algorithm. Sediment parameters were subsequently evaluated.

Scope

The evaluation was restricted to identifying the effect of rainfall parameters and ground cover on sediment yield.

The calibration procedure was developed using the first component of MULTSED which does not incorporate separate channels routing. Furthermore, because the channels in the watersheds used in this study were heavily vegetated swales, they were not a significant source of sediment. Therefore, channel erosion parameters were not calibrated.

Mode of Technology Transfer

This report documents tests and evaluations of the MULTSED simulation model for use in further research. Since MULTSED can model water and sediment yield from Army training lands, this report can be used at workshops for Army land managers.

2 DESCRIPTION OF MULTSED

MULTSED (Multiple Watershed Storm Water and Sediment Runoff Simulation Model) is a single event, distributed, deterministic simulation model. The model contains two basic components: a hydrologic and hydraulic routing component which computes storm runoff hydrographs, and a sediment component which computes sediment concentration hydrographs and sediment yield. These components are summarized below.

Runoff Component

MULTSED uses a watershed representation which consists of three types of homogeneous hydrologic units. The first type is a two-plane, single channel "open book" subwatershed which is used to simulate the upstream portions of a watershed. The second type, a channel unit, is used to represent downstream reaches of a river. The third type, single plane units, represent areas which produce lateral discharge into the channel units. The user determines the number and size of these units for a specific watershed.

Runoff is computed from the subwatershed and single plane units using an analytical solution to the kinematic wave equation. Input is the effective rainfall hyetograph. The flow is routed through the channel units using a numerical kinematic routing scheme.

Rainfall abstractions consist of interception and infiltration. Interception is satisfied during the initial part of the storm. Potential unit interception by canopy and ground cover is used together with the fraction of the area covered by each to determine the total interception. Potential infiltration is determined using the Green and Ampt equation written in an explicit incremental form.

Sediment Component

Sediment yield is determined by comparing potential sediment supply with sediment transport capacity. Actual sediment movement or deposition is determined by the lower value of either the available supply or the transport capacity.

The sediment size distribution is broken into a set of size ranges, each of which is treated independently. The total transport capacity is the sum of the transport rate for each size. Furthermore, the transport rate for each sediment size consists of bed load and suspended load rates. The bed load transport capacity, q_b, for overland flow is computed using the Meyer-Peter, Muller relationship.[2]

$$q_b = \frac{12.85}{\rho} (\tau - \tau_c)^{1.5} \qquad \text{[Eq 1]}$$

where τ = boundary shear stress due to grain resistence; τ_c = critical shear stress for the sediment size; and ρ = density of water.

[2] E. Meyer-Peter and R. Miller, "Formulas for Bed-Load Transport," *Proceedings*, 3rd Meeting of the IAHR (Stockholm, Sweden, 1948), pp 26-64.

The critical shear stress is determined using the Shields criterion:

$$\tau_c = \delta\gamma(S_s - 1)d_s \qquad \text{[Eq 2]}$$

where δ = a parameter dependent on flow conditions (i.e., Shields' critical shear parameter); S_s = the specific gravity of the sediment; d_s = the sediment size; and γ = the specific weight of water.

The boundary shear is determined by:

$$\tau = \frac{1}{8} K_o \nu\rho \frac{q}{y^2} \qquad \text{[Eq 3]}$$

where K_o = grain resistence parameter; q = water flow per unit width of flow area; y = mean depth of flow; and ν = kinematic viscosity of water.

The mean depth in turn is given by:

$$y = \frac{qK_g\nu}{8gS_o}^{1/3} \qquad \text{[Eq 4]}$$

where S_o = slope of ground surface; K_g = overall flow resistance factor which varies with the fraction of ground cover; and g = acceleration due to gravity.

The suspended load, q_s, computation is based on the Einstein approach:[3]

$$q_s = \frac{q_b}{11.6} \frac{S^{w-1}}{(1 - S)^w} [(\frac{V}{U_*} + 2.5) J_1 + 2.5 J_2] \qquad \text{[Eq 5]}$$

where U_* = shear velocity = $(gyS_o)^{1/2}$; V = mean velocity; w = $V_s/.4U_*$; V_s = settling velocity; S = a/y where a = distance related to particle size; and J_1 and J_2 are the result of integration of the equation describing the vertical concentration of sediment in the flow.

The total transport rate, q_t, is given by:

$$q_t = \sum_{i=1}^{N} (q_{si} + q_{bi}) i_s \qquad \text{[Eq 6]}$$

where i_s = fraction of sediment of size i; and N = total number of sizes.

[3] H. A. Einstein, "The Bed Load Function for Sediment Transport in Open Channel Flows," USDA Technical Bulletin No. 1026 (1950).

The total transport capacity, V_t for the entire event is:

$$V_t = \frac{T}{\gamma S_s} \int_o^{t_d} q_t \, dt \qquad \text{[Eq 7]}$$

where T = top width of the channel; and t_d = duration of runoff.

For channel transport capacity, the resistance factor for each sediment size is based on the ratio of sediment diameter to hydraulic radius. Other relationships for computing transport capacity are the same as for overland flow.

The sediment supply is provided by raindrop splash detachment and overland and channel flow detachment. Splash detachment is related to rainfall intensity, i, by:

$$V_r = a_1 \, i^2 \, L \, W \, (1 - \phi) \, A_b \qquad \text{[Eq 8]}$$

where V_r = the nonporous volume of sediment detached from a plane of length L and width W; ϕ = soil porosity; a_1 = erodibility factor of the soil; and A_b = fraction of bare soil.

Overland flow detachment is calculated using:

$$V_f = D_f(V_t - V_r) \qquad \text{[Eq 9]}$$

where V_f = detachment volume; D_f = flow detachment coefficient; and V_t = transport capacity. Channel flow detachment is calculated in a similar way with a different detachment coefficient.

The total available sediment supply, V_a, is the sum:

$$V_a = V_f + V_r \qquad \text{[Eq 10]}$$

Sediment yield is determined by the smaller of availability or transport capacity and is computed for each sediment size fraction.

Sediment routing is done analytically for subwatershed and plane units, giving total sediment yield. This is then distributed in time, in proportion to discharge for input, to channel units.

Channel routing is done numerically for each sediment size fraction based on the continuity equation:

$$\frac{\partial G_s}{\partial x} + \frac{\partial CA}{\partial t} + \frac{\partial Tz}{(1 - \phi)\partial t} = g_s \qquad \text{[Eq 11]}$$

where G_s = total transport rate by volume; C = concentration; z = depth of loose soil; A = flow cross sectional area; T = channel top width; and g_s = lateral sediment flow. This relationship is only valid for a limited depth of loose soil which is discussed in Simons et al.[4] Details of the numerical routing procedure are also discussed.

[4]D. B. Simons, R. M. Li, W. T. Fullerton, and T. R. Grindeland.

3 SENSITIVITY AND EVALUATION STUDY

Overview

The main thrust of this research centered around examining the sediment yield sensitivity of MULTSED to various input hyetographs, storm return periods and durations, and watershed cover conditions. The work broke down into two phases. Phase I examined the sediment yield sensitivity of the models to various input hyetograph shapes. Phase II examined the effects of varying storm duration, shape (less extensive than in Phase I), return period, and ground cover on sediment yield sensitivity.

Watershed Descriptions

Two watersheds are modeled, in this study: the Walnut Gulch Watershed in Arizona and the Four Mile Creek Watershed in Iowa.

Walnut Gulch Watershed

The Walnut Gulch Watershed is located in southeastern Arizona near Tombstone (Figure 1). Walnut Gulch is an ephemeral stream rising in the foothills of the Dragoon Mountains and joining the San Pedro River at Fairbank, Arizona. The Agricultural Reseach Service, USDA, has maintained 57.7 sq mi* of the Walnut Gulch Watershed as an experimental watershed since 1953. Figure 2 shows this experimental watershed subdivided into the subwatershed, plane, and channel units used by MULTSED.

The Walnut Gulch experimental watershed is uncultivated, semiarid rangeland. The vegetation of Walnut Gulch consists primarily of desert grasses and shrubs. The predominant soils in the watershed are gravelly loam and stony loam. The typical sediment size distributions for these soils are shown in Table 1. A complete and detailed description of the experimental watershed is available in Renard.[5]

Rather than examining the entire watershed, Phase I of this study modeled the watershed system made up of planes 25 and 26, subwatershed 33, and channel 9. In Phase II of this study, the response from subwatershed 33 was briefly examined. The channel in subwatershed 33 was modeled as a swale formed by the intersection of the two planes. It is 2800 ft long with a slope of 0.0153. The geometrical data for the MULTSED units are given in Table 2.

Based on the information provided by Renard and their own studies, Simons et al.[6] determined the Walnut Gulch Watershed hydrologic parameters listed in Table 3. For two of the parameters, initial soil moisture and canopy cover, ranges of values are listed. In this study, an initial soil moisture of 0.60 and a canopy cover of 38.0 percent is used for subwatershed 33, and an initial soil moisture of 0.70 and a canopy cover of 25.0 percent is used for planes 25 and 26. Typical data files for modeling this watershed by MULTSED are contained in Appendix A.

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*Metric conversions are provided on p 66.

[5] K. G. Renard, *The Hydrology of Semiarid Rangeland Watersheds*, ARS 41-162 (USDA, Agricultural Research Service, 1970).

[6] D. B. Simons, R. M. Li, W. T. Fullerton, and T. R. Grindeland.

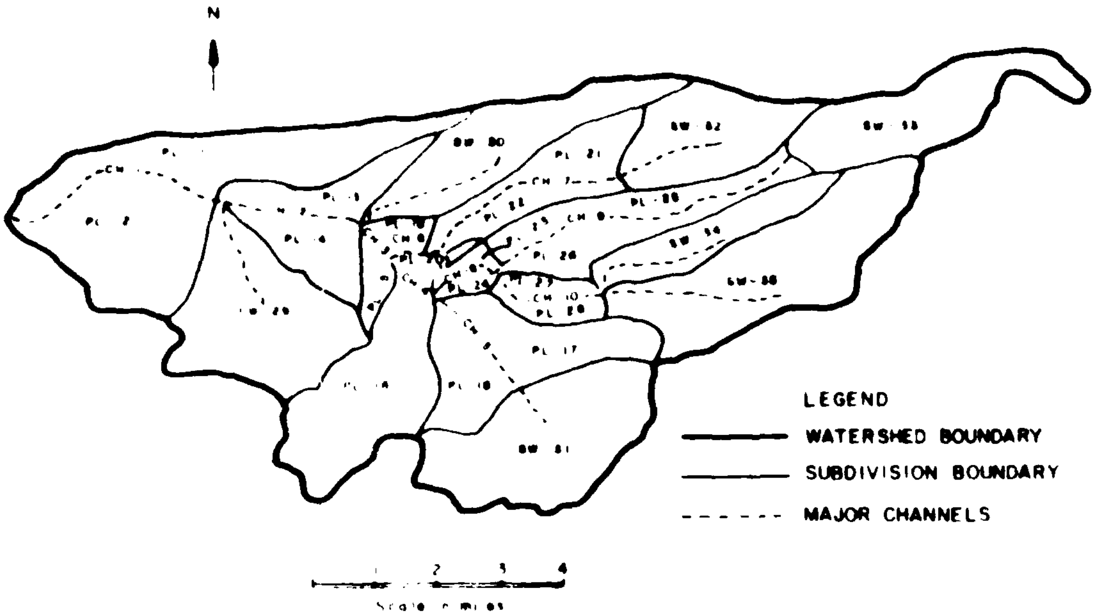

Figure 1. Location of the Walnut Gulch Watershed. (From D. B. Simons, R. M. Li, W. T. Fullerton, and T. R. Grindeland, *Storm Water and Sediment Runoff Simulation for a System of Multiple Watersheds—Vol II, Sediment Routing and Yield* [Colorado State University, October 1981], p 53.)

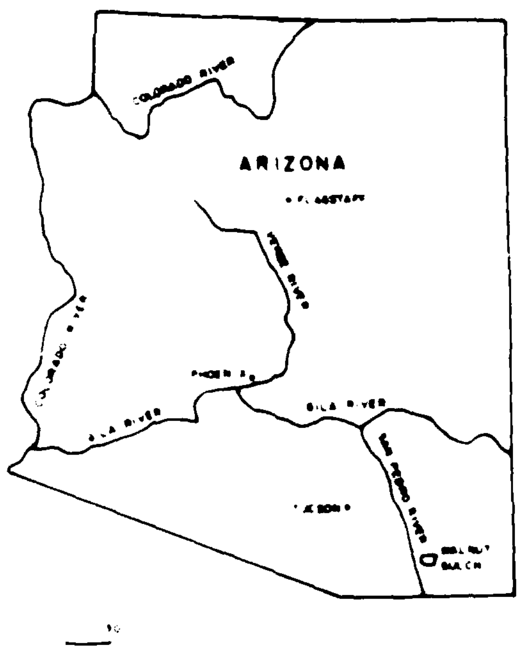

Figure 2. MULTSED response units for Walnut Gulch Watershed. (From D. B. Simons, R. M. Li, W. T. Fullerton, and T. R. Grindeland, *Storm Water and Sediment Runoff Simulation for a System of Multiple Watersheds—Vol II, Sediment Routing and Yield* [Colorado State University, October 1981], p 54.)

Table 1

Walnut Gulch Watershed Sediment Size Distribution*

Sediment Size (in.)	Plane and Subwatershed Unints; Fraction of Sediment Equal to or Finer Than Sediment Size	Channel Units; Fraction of Sediment Equal to or Finer Than Sediment Size
0.00008	0.15	0.10
0.002	0.55	0.16
0.02	0.72	0.22
0.04	0.82	0.28
0.06	0.89	0.33
0.08	0.94	0.46
0.12	0.97	0.62
0.16	0.99	0.80
1.0	1.00	1.00

*D. B. Simons, R. M. Li, W. T. Fullerton, and T. R. Grindeland, *Storm Water and Sediment Runoff Simulation for a System of Multiple Watersheds—Vol II, Sediment Routing and Yield* (Colorado State University, October 1981), p 60.

Table 2

Walnut Gulch Watershed Geometrical Data

Unit	Slope	Length (ft)	a_1*	b_1	a_2	b_2
PL25	0.050	916				
PL26	0.046	1492				
SW33 (left)	0.061	2097				
SW33 (right)	0.053	2310				
CH9	0.0153	29000	10.0	0.365	12.1	0.362

*a_1, b_1, a_2, b_2 are parameters used by MULTSED to describe the channel geometry.

Table 3

Walnut Gulch Watershed Hydrologic Parameters

Parameter	**Overland Flow**	**Channel Flow**
Hydraulic Conductivity	0.60 in./hr	1.0 in./hr
Average Suction	1.0 in.	2.0 in.
Porosity	0.40	0.40
Initial Soil Moisture*	0.60-0.90	0.60-0.90
Final Soil Moisture	1.0	1.0
Canopy Cover**	13.3-38.0%	NA
Canopy Cover Interception Value	0.05 in.	NA
Ground Cover	33.0%	NA
Ground Cover Interception Value	0.01 in.	NA
Soil Temperature	70.0 °F	NA
Resisance to Flow Manning's n	0.030	0.030
Resistance Factor for Plane Units	3000	NA

*In general, initial soil moisture conditions vary with each real storm.
**These values vary spatially in the watershed.

Four Mile Creek Watershed

Four Mile Creek originates in northwest Tama County, Iowa, near Lincoln (Figure 3). The portion of the Four Mile Creek Watershed of interest for this study is the subwatershed denoted ISU-2 (Iowa State University watershed number 2) in Figure 3. This small (15.5 acres) watershed has been monitored for storm runoff and erosion by Iowa State University (ISU) since 1976.

Figure 4 displays the topography and soil types of ISU-2 and its companion watershed ISU-1. The soils in ISU-2 are Tama silt loam and Colo-Judson silt loam, which are moderately permeable, dark colored soils with gently sloping topography up to eight percent in slope.[7] ISU-2 is an agricultural watershed which has been used to grow corn and soybeans on a yearly rotation basis. Each spring the residue from the previous year's crop is plowed and/or disked into the soil along with fertilizer, to provide a food base for the new crop and a small amount of erosion resistance beyond that of bare soil. Complete details on this watershed are available in the annual reports written by Johnson.[8]

The ISU-2 watershed was modeled as a single subwatershed in MULTSED and the channel was modeled as a swale formed by the intersection of the two planes. The channel itself is 1300 ft long with a slope of 0.02154 and the Manning's n is taken as 0.060. The left plane has an overland flow length of 240 ft with a slope of 0.05625, and the right plane has an overland flow length of 280 ft with a slope of 0.06744. The soil hydrologic parameters were determined using information provided by Park and Mitchell[9] or Johnson.[10] Table 4 contains a list of the ISU-2 hydrologic parameters used by MULTSED. An example of the resulting MULTSED data files is contained in Appendix A.

Sediment Yield Parameter Estimation

In addition to the hydrologic parameters of the watershed being modeled, MULTSED requires that certain sediment detachment parameters be determined and input. While the hydrologic parameters can mostly be determined by established tests and guidelines, the sediment yield parameters are much more subjective.

MULTSED requires the specification of Shields' critical shear parameter, a bed load transport coefficient, a bed load transport exponent, a rainfall splash exponent, and three detachment coefficients; rainfall splash, overland flow, and channel flow. As indicated in Chapter 2, the Meyer-Peter, Muller formulation is used to estimate the bed load transport rate. The formulation dictates that the bed load coefficient be 0.056 and bed load transport exponent be 1.5.

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[7]S. W. Park, J. K. Mitchell, and J. N. Scarborough, "Soil Erosion Simulation on Small Watersheds: A Modified ANSWERS Model," *Transactions of the ASAE*, Vol 25 (1982), pp 1581-1588.

[8]H. P. Johnson, *Development and Testing of Mathematical Models as Management Tools for Agricultural Non-Point Pollution Control, Annual Report 1976-77* (Agricultural Engineering Department, Iowa State University, 1978); H. P. Johnson, *Development and Testing of Mathematical Models as Management Tools for Agricultural Non-Point Pollution Control, Annual Report 1977-78* (Agricultural Engineering Department, Iowa State University, 1979).

[9]S. W. Park and J. K. Mitchell, *MODANSW (A Modified ANSWERS Model) User's Guide*, Agricultural Engineering Research Report (University of Illinois, February 1983).

[10]H. P. Johnson, 1976-77; H. P. Johnson, 1977-78.

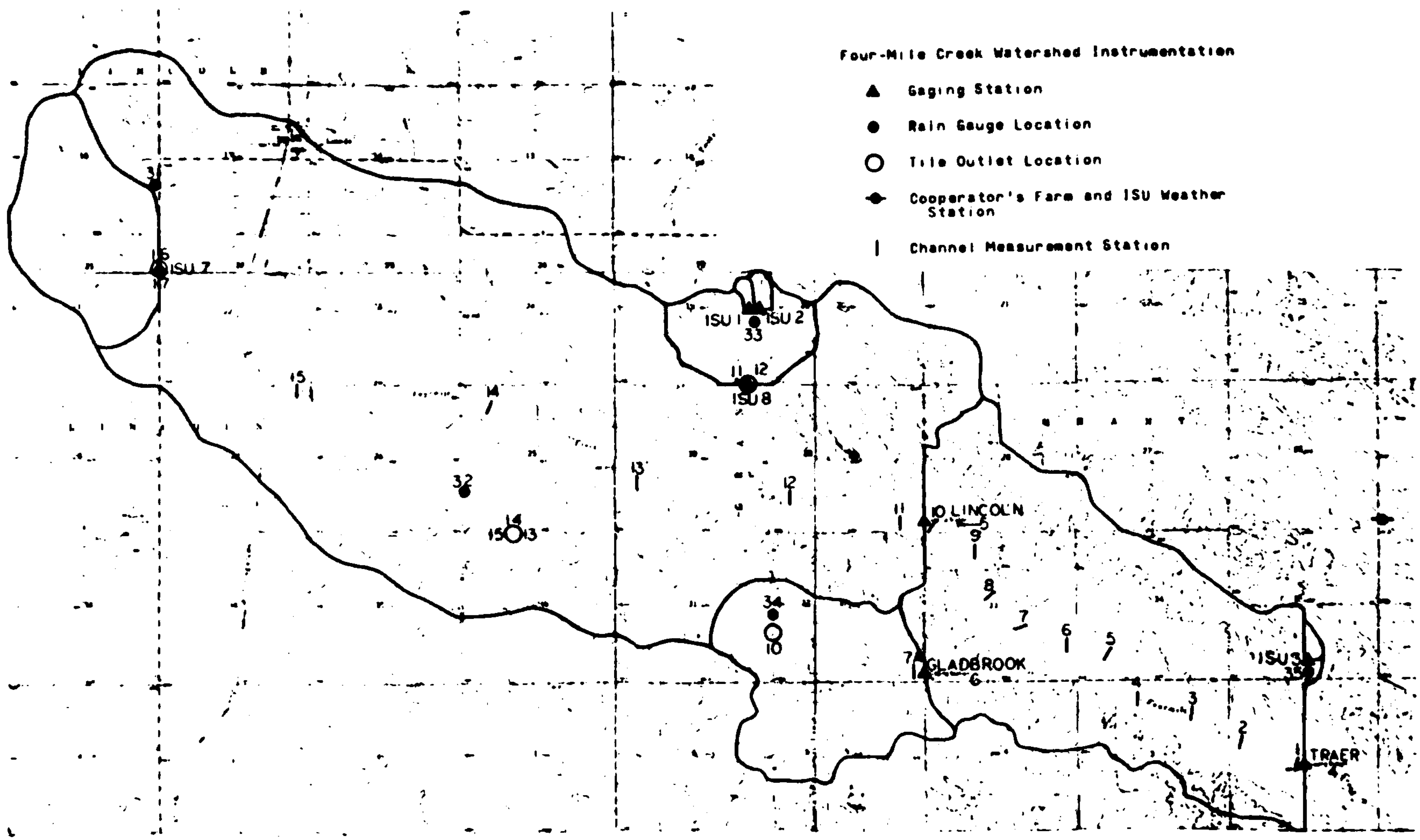

Figure 3. Location of Iowa State University Watershed #2 (ISU-2) in the Four Mile Creek Watershed. (From H. P. Johnson, *Development and Testing of Mathematical Models as Management Tools for Agricultural Non-Point Pollution Control, Annual Report 1976-77* [Agricultural Engineering Department, Iowa State University, 1978], p 13).

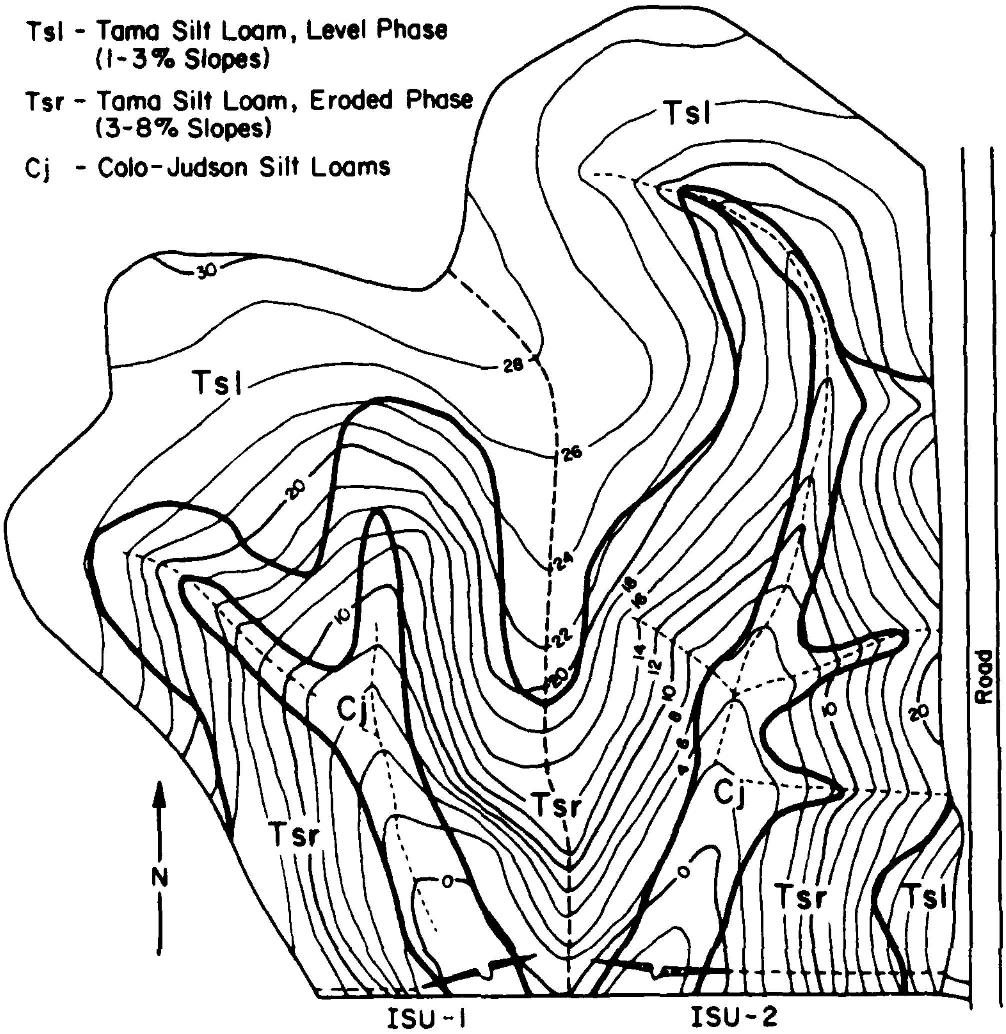

Figure 4. Topography and soils of Iowa State University watersheds numbers 1 and 2.

Table 4

ISU-2 Hydrologic Parameters for MULTSED

Parameter	Overland Flow Value
Hydraulic Conductivity	0.16 in./hr
Average Suction	3.5 in.
Porosity	0.475
Initial Soil Moisture	0.77
Final Soil Moisture	1.00
Ground Cover	1 or 99%
Ground Cover Interception Value	0.01 in.
Soil Temperature	70 °F

Actually, referring to the critical shear parameter as a Shields' parameter is somewhat of a misnomer. The Meyer-Peter, Muller formulation was originally derived by observing the relationship between bed motion and flow energy exerted on the bed, so it is not truly a shear stress relation as is commonly reported in the literature. However, the shear stress form may be obtained through several simple assumptions. The limiting dimensionless shear stress and the coefficient, 12.85 (Equation 1) were obtained empirically by taking a linear "best fit" of data plotted on a dimensionless plot comparing flow energy exerted on the bed and the bed load. For their data, Meyer-Peter and Muller found the limiting value of the dimensionless shear stress, to be 0.047. Theoretically, Shields' critical shear parameter should be fixed at 0.047 or else the coefficient value 12.85 no longer represents a true "best fit." However, practical experience has shown that keeping the coefficient at 12.85 and allowing the critical shear parameter to correspond to Shields' diagram provides reasonable results. This is especially true for steeper sloped (S = 3 to 20 percent) channels.[11] Nevertheless, in this study the value 0.047 was used.

The rainfall splash exponent may be safely taken as 2. This approximate relation was noted as early as 1939 when Horton[12] reported that the erosion rate for rainfall plot experiments under stable flow conditions varies nearly as the square of the runoff intensity and the 2.2 power of the rainfall intensity. In 1969, Meyer and Wischmeir[13] reasoned the splash detachment rate to be proportional to the square of the rainfall intensity based on considerations of the rainfall intensity and its kinetic energy. Later, Meyer[14] confirmed this reasoning based on the results of hundreds of rainfall plot experiments.

Only the values of the detachment coefficients remain to be determined by the modeler. The problem is that very little information is available to aid the modeler in estimating these coefficients. In Chapter 5, a method for calibrating MULTSED to available rainfall, runoff, and sediment yield data is discussed. Furthermore, the results of calibrating MULTSED for 17 storms on 5 small midwestern watersheds are presented to serve as a guideline for selecting reasonable detachment coefficient values. Unfortunately, the initial rainfall sensitivity analysis was completed well before the calibration work was performed. Therefore, the detachment coefficient values for Walnut Gulch were taken as 0.01, 1.0, and 1.0 for rainfall, overland flow, and channel flow, respectively, as reported by Simons et al.[15] While for ISU-2, the detachment coefficient values were chosen such that transport capacity is the limiting factor in the sediment yield calculations.

By choosing the detachment coefficients to be so large that the sediment transport capacity becomes the limiting factor in the sediment yield calculations, the study of the sensitivity of MULTSED to changes in ground cover is somewhat incomplete. This incompleteness is in the failure to account for the rainfall impact energy absorbed by the cover and the subsequent reduction of the rainfall splash detachment. However, this

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[11] G. M. Smart, "Sediment Transport Formula for Steep Channels," *Journal of Hydraulic Engineering*, Vol 110, No. 3 (1984), pp 267-276.

[12] R. E. Horton, "Analysis of Runoff-Plot Experiments with Varying Infiltration Capacity," *Transactions, American Geophysical Union*, Vol 20 (1939), pp 693-711.

[13] L. D. Meyer and W. H. Wischmeir, "Mathematical Simulation of the Process of Soil Erosion by Water," *Transactions of the ASAE*, Vol 12, No. 6 (1969), pp 754-762.

[14] L. D. Meyer, "How Rain Intensity Affects Interill Erosion," *Transactions of the ASAE*, Vol 24, No. 6 (1981), pp 1472-1475.

[15] D. B. Simons, R. M. Li, W. T. Fullerton, and T. R. Grindeland.

study does account for reduced erosion due to the increased surface roughness pertaining to increased ground cover. These facts are evidenced by the following discussion of the physical effects of cover on erosion and how MULTSED accounts for these factors.

One would expect canopy cover physically to affect the amount of water intercepted and the raindrop impact energy (and thus the splash detachment). In MULTSED, canopy cover only effects the amount of water intercepted. Therefore, it is up to the modeler to compensate for the loss of impact energy by reducing the rainfall splash detachment coefficient.

One would expect ground cover physically to affect the amount of water intercepted, the raindrop impact energy, and the surface roughness. Increased surface roughness causes the runoff velocity to decrease and depth to increase; this decreases the flow's ability to detach and carry sediment. Furthermore, the deeper, slower flowing water is subject to more infiltration. Thus, when surface roughness increases, less soil is detached and there is less water available to carry off sediment. MULTSED accounts for this by defining the overland flow resistance:

$$K_g = K_\ell + (ADW - K_\ell)C_g^2 \qquad \text{[Eq 12]}$$

where Kg = the parameter describing the overall overland flow resistance; ADW = the parameter describing the maximum resistance for the area (Cg = 1.0) (Input by the user); K_ℓ = the parameter describing the minimum resistance for the area (Cg = 0.0) (Chosen internal to the program); and Cg = the fraction of ground cover. Thus, as the amount of ground cover increases, surface roughness increases. MULTSED also accounts for the ground cover's effects on interception. Therefore, only the reduction of impact energy must be compensated for by the modeler.

Based on these physical considerations, the following conclusions can be made. It would appear that the rainfall splash detachment is a function of the amount of ground and canopy cover and their respective heights (heights relate to energy loss). The overland flow detachment coefficient appears to be primarily a function of soil type, incorporated residue, and surface conditions. The effects of ground cover on overland flow erosion are accounted for in the overland flow resistance.

The value of the maximum resistance to overland flow parameters, ADW, must be input by the user. Woolhiser[16] presents a table in which various surface and cover conditions are related to ranges of ADW values. The condition of 1 percent cover was believed to correspond to the high end of the "bare clay-loam soil (eroded)" range which is 500. The condition of 99 percent cover was believed to correspond to the middle of the "short grass prairie" range which is about 5000.

Rainfall Input for Phase I

The goal of Phase I was to examine the sensitivity of MULTSED to various input hyetograph shapes. Phase I broke down into three parts: sensitivity to the time of the

[16] D. A. Woolhiser, "Simulation of Unsteady Overland Flow," *Unsteady Flow in Open Channels*, K. Mahmood and V. Yevjevich (Eds.) (Water Resources Publications, Fort Collins, Colorado, 1975).

hyetograph peak, sensitivity to the magnitude of the hyetograph peak, and an examination of the linearity of the model.

The sensitivity of the model with respect to the time of the hyetograph peak was examined by modeling three storms of equal rainfall depth, 2 in.: an advanced peak storm (Table 5, #1), a symmetrical peak storm (#2), and a delayed peak storm (#3).

The sensitivity of the model with respect to the magnitude of the hyetograph peak was examined by modeling three storms of equal depth, 2 in.: a uniform storm (Table 5, #4), a symmetrical storm with a 6 in./hr peak (#2), and a symmetrical storm with an 8 in./hr peak (#5).

Before discussing the examination of model linearity, a quick review of the principle of linearity is appropriate. A linear model is one whose output follows the principle of superposition. This principle states that if input A yields output X and input B yields output Y, then the system is linear if an input of A plus B yields an output of X plus Y.

The possible linearity of the models was examined by comparing the results of modeling three uniform storms: one with a 2 in. depth and a 35 minute duration (Table 5, #4), one with a 4 in. depth and a 35 minute duration (#6), and one with a 4 in. (101.6 mm) depth and a 70 minute duration (#7).

Rainfall Input for Phase II

The goal of Phase II was to evaluate the model's sensitivity to varying ground cover, hyetograph shape, and rainfall depth, duration, and return period using the ISU-2 watershed.

In regard to the sensitivity to varying cover conditions, two extreme cases were studied: 1 percent soybean cover and 99 percent soybean cover. Complete details on parameter determination for both of these aspects of Phase II have been presented earlier in this chapter. Thus, only the rainfall input aspects must still be discussed.

The values of the rainfall depth, duration, and return period are intertwined. Fredrick et al.[17] and Technical Paper No. 40[18] were used to find the rainfall depth for a storm in Tama County, Iowa, with a given return period and a given duration, td. The return periods--2, 5, 10, and 50 years--provide coverage of the range which should contain the ultimately chosen design storm return period. It was felt that a certain combination of rainfall depth, duration, and the resulting intensity would yield an ultimate or maximum sediment yield. The duration corresponding to the maximum was thought to possibly be related to the watershed's time of concentration, tc. ISU-2's time of concentration was estimated to be 15 minutes (see Appendix B). To provide good coverage of the possible range for the maximum, the following storm durations were chosen: 5, 10, 15, 30, 60, and 120 minutes. Table 6 contains the rainfall depths for the storm durations and return periods studied.

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[17] R. H. Fredrick, V. A. Meyers, and E. P. Auciello, *Five- to 60-minute Precipitation Frequency for the Eastern and Central United States*, NOAA Technical Memorandum NWS HYDRO-35 (National Weather Service, Silver Spring, MD, June 1977).

[18] D. M. Hershfield, *Rainfall Frequency Atlas of the United States*, Technical Paper No. 40 (U.S. Department of Commerce, Weather Bureau, Washington, D.C., May 1961).

Table 5

Hyetograph Shapes

Time, min	#1 Intensity in./hr	#2 Intensity in./hr	#3 Intensity in./hr
0-5	2.0	2.0	2.0
5-10	6.0	3.0	2.0
10-15	5.0	4.0	3.0
15-20	4.0	6.0	4.0
20-25	3.0	4.0	5.0
25-30	2.0	3.0	6.0
30-35	2.0	2.0	2.0

Time min	#4 Intensity in./hr	#5 Intensity in./hr	#6 Intensity in./hr
0-5	3.429	1.0	6.86
5-10	3.429	2.5	6.86
10-15	3.429	2.5	6.86
15-20	3.429	8.0	6.86
20-25	3.429	4.5	6.86
25-30	3.429	2.5	6.86
30-35	3.429	1.0	6.86

Hyetograph #7 was uniform with an intensity of 3.429 in./hr (87.1 mm/hr) and a duration of 70 min.

Table 6

ISU-2 Rainfall Depths for Phase II

		Rainfall depth, in.			
td (min)	td/tc	2-year storm	5-year storm	10-year storm	50-year storm
5	0.33	0.446	0.535	0.600	0.769
10	0.67	0.700	0.862	0.978	1.275
15	1.00	0.875	1.088	1.239	1.625
30	2.00	1.240	1.580	1.830	2.290
60	4.00	1.540	2.000	2.290	2.900
120	8.00	1.840	2.320	2.700	3.430

Although Phase I provided sufficient information about the model's sensitivity to various input hyetograph shapes, additional information regarding the effect of the hyetograph shape could be useful. Therefore, the Phase II analysis was performed using both a uniform hyetograph and a symmetrical, triangular hyetograph.

Since MULTSED requires that the hyetograph be input as block data, the symmetrical, triangular hyetograph had to be approximated. Figure 5 shows two possible schemes for approximating this triangular hyetograph. Each of these schemes has clear deficiencies. Scheme A preserves the proper storm duration, but it reduces the peak intensity. Scheme B preserves the peak intensity, but it shrinks the storm duration. In Phase I, the magnitude of the sediment yield seemed to be related to the peak intensity of the storm. Therefore, it is more important to preserve the peak intensity. Scheme B was used.

Upon conducting the sensitivity runs on ISU-2, an optimum combination of storm rainfall depth and duration which produces a maximum sediment yield was found. To determine if the critical duration was a function of the watershed's time of concentration, a similar yet simpler sensitivity analysis of subwatershed 33 of the Walnut Gulch Watershed was performed. In the sensitivity analysis of subwatershed 33, the modeled surface cover conditions were the same as in Phase I and only the uniform hyetograph was examined.

Subwatershed 33's time of concentration was estimated to be 120 minutes (see Appendix B). Therefore, the following durations were examined as a representative range: 15, 30, 60, 120, 180, and 360 minutes. The return periods examined were the same as for ISU-2. Using Technical Paper No. 40, the rainfall depths for the desired storm events on Walnut Gulch with durations between 30 and 360 minutes were determined. These values were plotted on semilog paper and a curve was fitted through them. This curve was then extrapolated backwards to provide an estimate of the 15 minute duration storm. The storm rainfall depths for all the durations and return periods studied are listed in Table 7.

Effect of Hyetograph Shape on Sediment Yield—Phase I

This initial study involved observing of the effects of arbitrary rainfall hyetograph shapes on sediment yield. Table 5 describes the various hyetographs. The total depth for hyetographs 1 through 5 was 2.0 in. For hyetographs 6 and 7, the total depth was 4.0 in.

The results shown in Table 8 indicate that there is no significant variation in sediment yield using hyetographs 1 through 4. Hyetograph 5, which is characterized by a very high intensity at midduration, does evoke approximately an eight percent increase in sediment yield. These results indicate the model is not highly sensitive to hyetograph shape, other hyetograph parameters being held constant. However, the duration of the rainfall for hyetographs 1 through 6 was only about 0.2 tc, which could serve to suppress sensitivity to hyetograph shape.

A comparison of hyetograph 4 and 6 results indicates linearity since the hyetographs are proportional. The sediment yield increased by 4.5, for an increase in intensity by a factor of 2.0. This shows significant nonlinearity with respect to average intensity for a constant duration.

A comparison of hyetograph 4 and 7 results shows the nonlinear effect of doubling the duration, keeping the intensity constant.

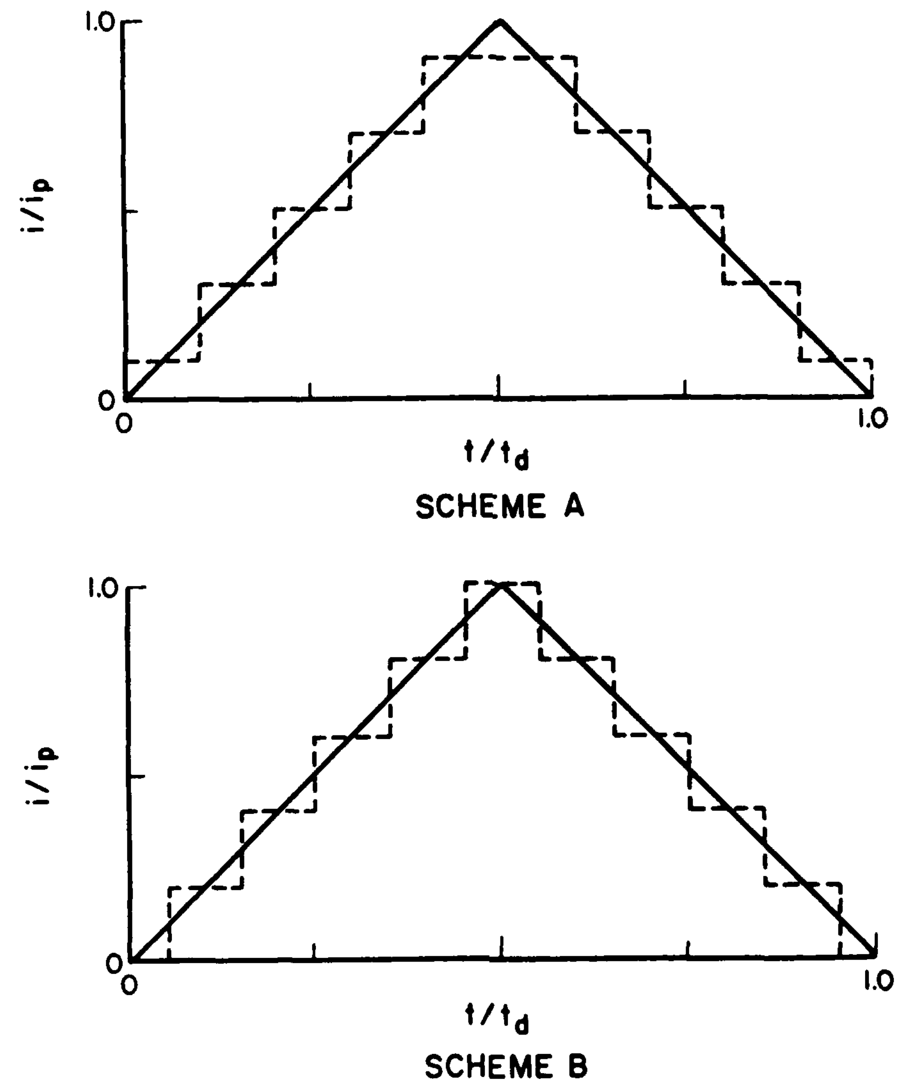


Figure 5. Schemes for approximating the symmetrical, triangular hyetograph.

Table 7

Walnut Gulch Rainfall Depths for Phase II

td (min)	td/tc	Rainfall Depth, in. 2-year storm	5-year storm	10-year storm	50-year storm
15	0.125	0.75	1.05	1.28	1.57
30	0.25	0.90	1.30	1.54	2.00
60	0.50	1.15	1.67	1.90	2.60
120	1.00	1.34	1.80	2.20	3.00
180	1.50	1.44	2.01	2.37	3.18
360	3.00	1.62	2.25	2.64	3.66

Table 8

Hyetograph Sensitivity—Walnut Gulch Watershed

Hyetograph Number	Sediment Yield $10^3 \frac{lb}{acre}$	Maximum Q $\frac{cfs}{acre}$
1	4.03	0.90
2	4.00	0.92
3	4.03	0.91
4	4.03	0.92
5	4.30	0.97
6	17.99	3.36
7	12.22	2.33

Effect of Rainfall Depth and Duration on Sediment Yield

A data file describing the ISU-2 watershed was established and run for a series of storm events based on local depth-duration-frequency data as described earlier. Two hyetograph shapes were used for these runs: uniform and symmetrical triangular.

Results are shown in Figure 6. All curves are characterized by a sharp rise in sediment yield with increasing duration up to a relative duration (duration/time of concentration, td/tc) of approximately 2 to 4. A well defined maximum is present at about td/tc = 3 (45 minutes duration). These results are independent of hyetograph shape and percent ground cover.

Figure 7 shows the results for subwatershed 33 of Walnut Gulch for a uniform hyetograph. The drainage area for this catchment is 2832 acres or 167 times larger than the ISU-2 watershed. Also, the rainfall depth for a given return period and duration is much lower than for the Iowa location. When this is combined with the high infiltration capacity of the local soil, it is quite possible for all rainfall to infiltrate. This is why the curves in Figure 7 fall to zero. As the duration increases, the average intensity falls, eventually becoming so low that abstractions are not satisfied, and therefore, runoff and sediment yield are prevented. Figure 7 shows a well-defined maximum yield corresponding to relative durations of less than 0.5. This contrasts sharply to the critical relative durations for the ISU-2 watershed, on the order of 2 to 4. Thus, it is a combination of watershed properties and rainfall characteristics that determines the duration which produces maximum yield. It should be noted that if a tc of 70 minutes is used, as estimated by the second method in Appendix B, the critical relative duration would be about 1.0, a more reasonable result.

It is interesting to observe that for both watersheds, the critical (absolute) duration was about 30 minutes, despite the differences in tc. This duration produced the best combination of depth and duration (average intensity) for producing sediment yield. Given the great differences in size and nature of the two watersheds, this could imply that a 30 minute duration could be used to produce the maximum yield from a variety of watersheds. However, a firm conclusion on this is not justified on the basis of the analysis of only two watersheds.

Effect of Ground Cover on Sediment Yield

Ground cover is a potentially significant management parameter. To illustrate the effect of this parameter, the ratio of the sediment yield for 1 percent cover to 99 percent cover was computed based on the results of Figure 6. Figure 8 shows the results. The return period effect was large enough to identify an upper and lower bound corresponding to 2 and 50 year return periods respectively. The curves shown are for a uniform rainfall hyetograph. The results for the triangular hyetograph fall within the limits for the uniform hyetograph.

Figure 8 also shows increased sensitivity for relative durations below 2, but small variation in the yield ratio for higher durations. This shows that ground cover is an important parameter and that its relative effect is not significantly affected by hyetograph shape or magnitude and duration of rainfall except for relatively short duration events.

Effect of Hyetograph Shape on Sediment Yield—Phase II

The results of the Phase I analysis of rainfall temporal effects are placed in a better perspective by considering a wide spectrum of rainfall magnitude and duration. Figure 6 shows a definite effect of hyetograph shape, with the triangular distribution producing greater sediment yield. To illustrate the effect of hyetograph shape more clearly, the ratio of the yields for the triangular to uniform hyetographs for various durations are shown in Figure 9. The effect of return period was small and average values were plotted for each duration.

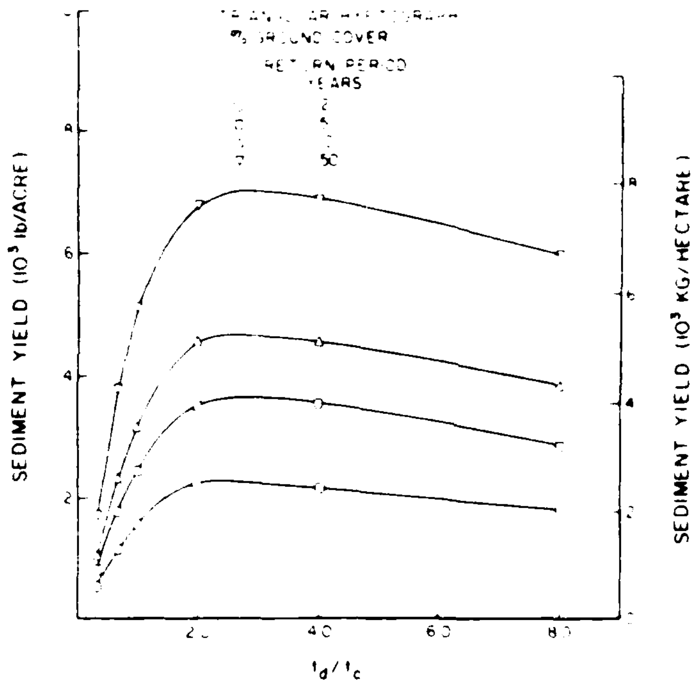
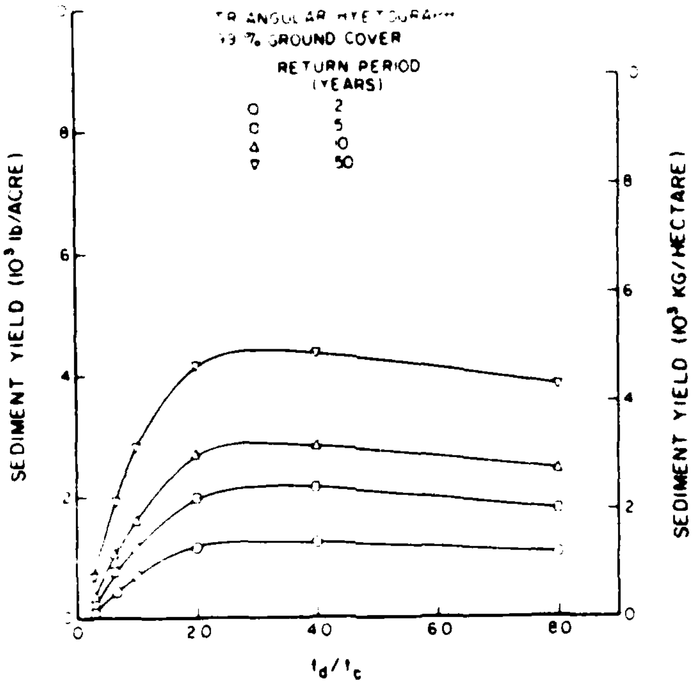


Figure 6. Sediment yield vs. relative duration for ISU-2 watershed.



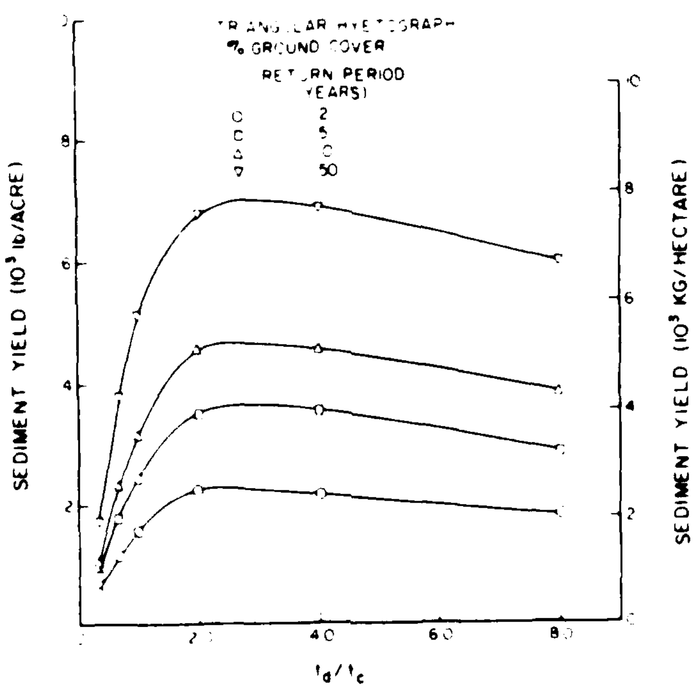


Figure 6 (Cont'd).

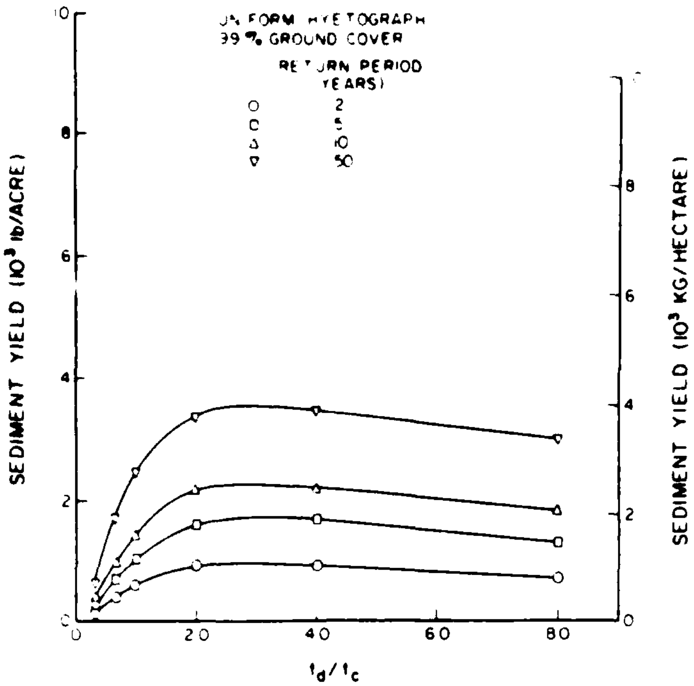


Figure 6 (Cont'd).

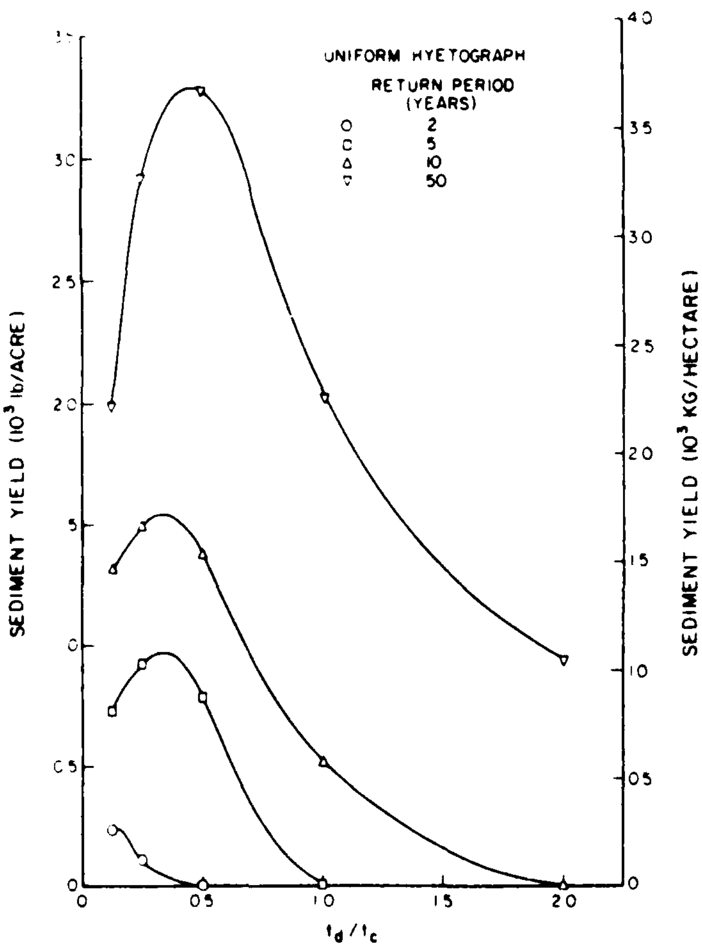


Figure 7. Sediment yield vs. relative duration for Walnut Gulch Subwatershed 33.

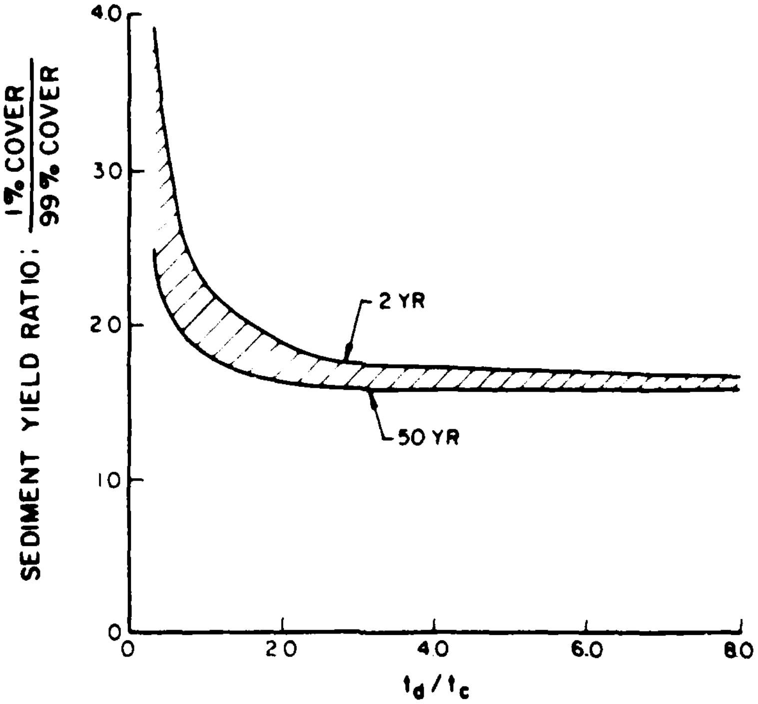


Figure 8. Ground cover sediment yield ratio vs. relative duration for ISU-2 watershed.

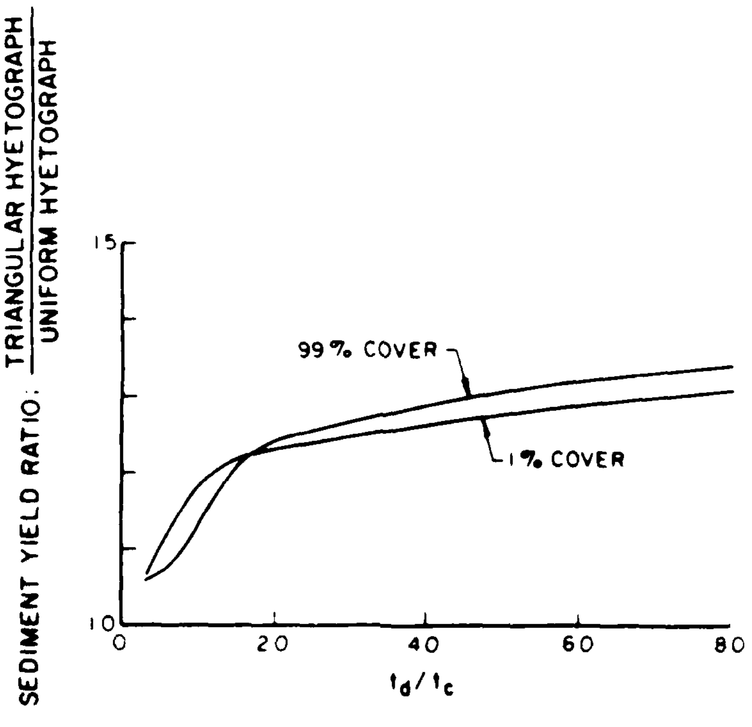


Figure 9. Hyetograph shape sediment yield ratio vs. relative duration for ISU-2 watershed.

4 DESIGN STORM SELECTION

Rainfall Parameters and Effect on Sediment Yield

Traditionally, rainfall data are analyzed and presented in terms of depth (intensity)-duration-frequency maps or tables. For a given frequency or return period, the rainfall intensity decreases as the duration increases.

In the MULTSED model, nonchannel erosion is initiated by raindrop splash detachment and overland flow detachment. Raindrop splash detachment is proportional to the square of the rainfall intensity. Overland flow detachment is proportional to the difference between the transport capacity of the flow and the sediment supply provided by rainfall detachment. Thus, erosion is increased by higher rainfall intensity as well as increased duration.

Given the shape of a typical intensity-duration rainfall curve as described above, and the nature of the erosion process as represented in MULTSED, the potential for a tradeoff exists between intensity and duration which would maximize erosion for a given return period. Furthermore, the time of concentration of the watershed or subwatershed under consideration also could be an important guideline since potential maximum erosion may require the entire watershed to be contributing to runoff. It is therefore reasonable to expect that a useful storm event for producing significant erosion would have a maximum intensity consistent with a duration which is at least equal to the time of concentration.

Sediment Yield-Rainfall Parameter Study

In Chapter 3, two watersheds were used to study the effect of rainfall parameters on sediment yield. As a follow-up, five additional watersheds were used to study the effect of rainfall duration. A uniform rainfall hyetograph was adopted and thus various temporal patterns were not examined. Basic watershed data are presented in Table 9 and are described in more detail in Chapters 5 and 6. The time of concentration was estimated using the model itself (as described in Appendix B) and was independently checked.

The results, shown in Figure 10, are displayed in terms of the ratio of the duration of the rainfall to the time of concentration, td/tc versus the ratio of the sediment yield to the sediment yield for a duration equal to the time of concentration, Y/Ytc. The results are consistent except for the Lawson Creek Watershed which is very small and requires a relatively longer rainfall to achieve maximum sediment yield.

Figure 10 shows that relative durations (td/tc) in the range of 1.0 to 2.0 produced maximum sediment yield, with the exception of the Lawson Creek Tributary 1.

Intensity-duration rainfall data from HYDRO-35 and TP-40 were used with a return period of 5 years. Model parameter values from previous calibration work were used.

Recommended Rainfall Parameters

The magnitude or return period for the reference event or design storm is somewhat arbitrary since consistent parameter effects on sediment yield were observed

Table 9

Watershed Data

Name	Identifier	Location	Area (acres)	Time of Concentration (min)
Four Mile Creek	ISU-1	Tama Co., IA	12.2	20
Lawson Creek Tributary 1	LCT-1	Sheffield, IL	3.25	10
Highland Silver Lake 1	HSL-1	Highland, IL	263.2	170
Highland Silver Lake 2	HSL-2	Highland, IL	1078.8	190
Laguna	L-2	Albuquerque, NM	40.5	12

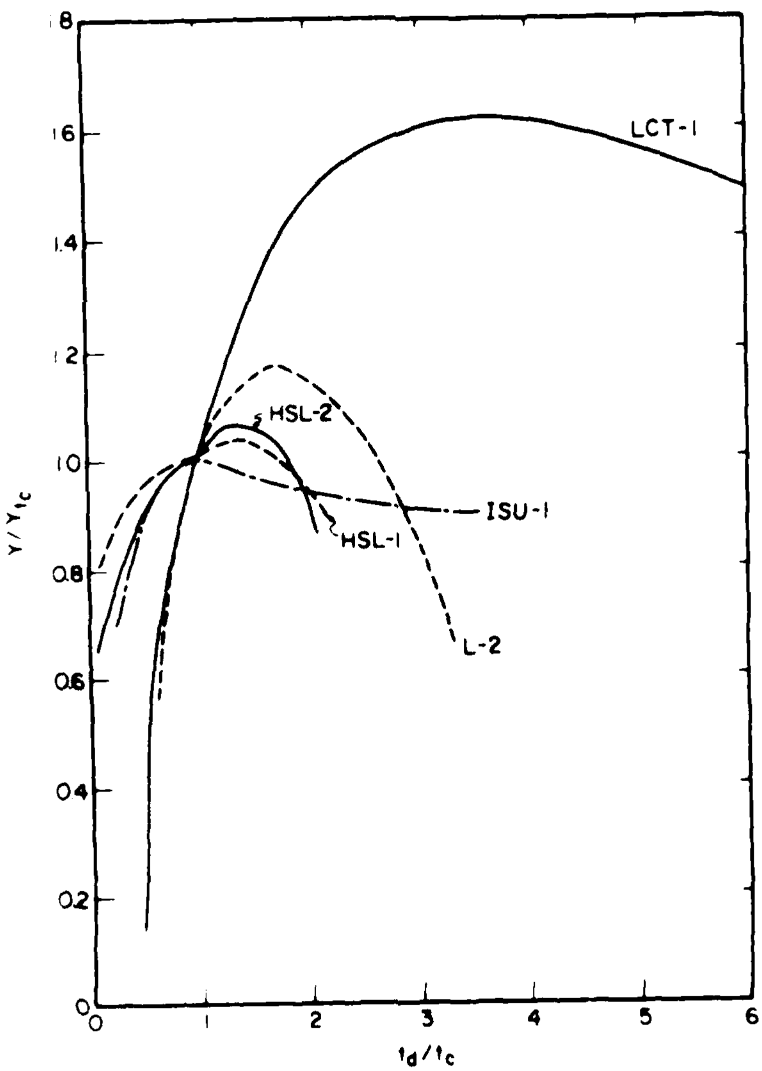


Figure 10. Sediment yield ratio vs. relative duration.

for a constant return period. A return period of 5 years would produce significant intensity which would involve all components of the model in computing sediment yield.

The rainfall temporal distribution (hyetograph) of the reference event is not of great importance for evaluating land management techniques. The triangular hyetograph produces consistently higher sediment yields than does the uniform hyetograph and is more realistic, but it is unlikely that any conclusions regarding land management techniques will be changed because of the hyetograph used in the model. Hence, it is more important to be consistent in the hyetograph shape used. Yen and Chow have recommended the triangular hyetograph for designing small drainage structures,[19] but state that for larger watersheds, the storage effect significantly reduces the effect of rainfall intensity variations. However, with the soil detachment process being sensitive to rainfall intensity, sediment yield may show more sensitivity to rainfall intensity even on larger watersheds, so their recommendation may not carry over from runoff to sediment yield. On the other hand, the sediment transport capacity is often the controlling factor in the sediment yield, and it is definitely a function of discharge. Therefore, if the design discharge is relatively unaffected by the hyetograph shape for larger watersheds, it may be that the sediment transport capacity and hence sediment yield are similarly unaffected. Considering the experience described in this report, a uniform distribution should be acceptable for management purposes. This should not be confused with simulation of actual events since uniform rainfall distributions are unlikely in nature.

The duration of the reference event is important if maximum yield is desired. Sediment yield is not as sensitive to duration as is peak runoff because of the contribution of the soil detachment and sheet erosion processes. Soil detachment is sensitive to rainfall intensity, while sheet erosion is sensitive to duration. Thus, a tradeoff between intensity and duration is required to maximize sediment yield. Within the context of the depth-duration-frequency description of rainfall data, the simulations reported above indicate that a duration of 1 to 3 times the time of concentration of a subwatershed will produce maximum sediment yield for the selected return period.

Recommended Procedure

1. It is recommended that the erosion from subwatersheds or planes be examined rather than the net yield from a system containing channel elements. This is because the latter can produce deposition which will mask the effects of management practices which may be tested in the model.

2. The time of concentration of the watershed unit should be estimated. This can be done using the model itself (as described in Appendix B) or using existing analytical procedures.

3. Rainfall data for the area in the form of intensity-duration-frequency are required. Local data are best, but national data sources are available.[20]

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[19] B. C. Yen and V. T. Chow, "Design Hyetographs for Small Drainage Structures," *Journal of the Hydraulics Division, ASCE*, Vol 106, No. HY6 (1980), pp 1055-1076.

[20] R. H. Fredrick, V. A. Meyers, and E. P. Auciello; D. M. Hershfield; J. F. Miller, R. H. Fredrick, and R. J. Tracey, "Precipitation Frequency Atlas of the Conterminous Western United States (by states)," *NOAA Atlas 2*, 11 vols (National Weather Service, Silver Springs, MD, 1973).

4. The model should be calibrated (as described in Chapters 5 and 6) and run using several combinations of intensity and duration consistent with a 5-year return period. A uniform intensity rainfall pattern is recommended, since it is simple to use yet was found to produce the desired sensitivity as well as other more realistic rainfall patterns. The duration which produces the maximum sediment yield from the watershed unit should be selected as the critical duration.

5 CALIBRATION PROCEDURE FOR SMALL WATERSHEDS

Goal of Calibration

The overland erosion process is so complex that an adequate relation to describe it has not been derived. Therefore, modelers have resorted to using empirical relations to describe the overland sediment detachment process. To estimate the actual detached sediment supply available for transport, these empirical relations need correction factors known as detachment coefficients. The sediment yield is generally taken as the lesser of the sediment supply and the overland flow sediment transport capacity, which is estimated using modified versions of equations derived to describe sediment transport in open channels. Currently, the primary sources of information regarding the detachment coefficients are rainfall simulator tests on small field plots. While these tests are quite useful for determining the practical range of detachment coefficient values, certain questions exist regarding the appropriateness of using detachment coefficients from small plots in modeling larger watersheds. This report develops a procedure for calibrating both water and sediment yields, and uses this procedure to calibrate detachment coefficient values for storm events on several small watersheds in the midwestern United States. A brief discussion of calibration for larger watersheds is given in Chapter 6.

Basic Calibration Procedure

Both the overland flow and channel flow sediment transport capacities are a function of the flow rate. Therefore, ideally, it is desirable to perform the calibration in a stepwise fashion, wherein the "optimal" hydrologic fit is obtained and then the detachment coefficients are optimized based on the transport capacities corresponding to the "best fit" hydrograph. Unfortunately, the optimal resistance coefficient values for the hydrologic "best fit" were generally too large to allow sufficient flow velocity. Hence, the calculated sediment transport capacities were not large enough to reproduce the measured sediment yield. This high resistance is necessary to reproduce the measured time lag between the rainfall hyetograph and the runoff hydrograph. Thus, when performing the hydrologic calibration, it became necessary to artificially reduce the measured time lag between the rainfall hyetograph and the runoff hydrograph to obtain reasonable (i.e., "close" to measured) runoff and sediment yield.

MULTSED simulates the hydrograph resulting from a storm event as a function of six hydrologic parameters: resaturated hydraulic conductivity, KH; average capillary suction, $-\psi$; potential ground cover and canopy cover interception volumes, VG and VC, respectively; Manning's n for channel flow; and the maximum overland flow resistance coefficient, ADW. The "best" hydrologic fit is determined primarily on the basis of formal optimization of these parameters such that the sum of the squares difference between the measured and simulated hydrographs is minimized, i.e.,

$$\mathrm{MIN} \sum_t (Q_{mt} - Q_{st})^2 \qquad \text{[Eq 13]}$$

where Q_{mt} = the measured discharge at time t; and Q_{st} = the simulated discharge at time t. It was found that generally the simulated hydrograph which minimized the sum of squares difference provided an equally good fit in terms of matching simulated and measured peak discharges and total runoff volumes (generally within 20 percent for all 3

fit quality indicators). Upon choosing an initial time shift (i.e., artificial reduction in the measured time lag), Equation 13 is optimized and the calibrated hydrologic parameters are used to simulate the sediment yield. If the overland and channel sediment transport capacities are sufficient to generate the measured sediment yield, then the detachment coefficients will be calibrated by iterating until the measured total sediment yield is matched. Otherwise, the hydrologic parameters are adjusted or possibly recalibrated until the overland and channel sediment transport capacities are sufficient and then the detachment coefficients are calibrated.

Hydrologic Calibration Model

The complete MULTSED model consists of three components. The first component analytically determines the runoff hydrographs from simple subwatersheds along the hydrologic boundary of the watershed, and also from the overland flow planes along the downstream reaches of the stream network, by using the method of characteristics solutions to the kinematic wave flow routing problem. The sediment transport capacity for both the overland flow and the channel flow is estimated using Einstein's total load relation with the Meyer-Peter, Muller bed load equation substituted for Einstein's bed load relation. The second component merely reorganizes the output from the first component for more efficient use in the third component. The third component routes the water and sediment generated from the subwatersheds and planes in the first component through the channel network using a nonlinear iterative solution to the kinematic wave flow routing problem. Once again, the combined Einstein and Meyer-Peter, Muller relation is used to determine the channel transport capacity. Since the third component uses a numerical solution to the flow and sediment routing, it can account for some natural sediment transport processes which the analytical solution in the first component cannot, i.e., the natural suspended sediment settling process and channel bed armoring.

In the analytical method (component 1), the total sediment yield is constrained to a maximum equal to the channel sediment transport capacity. Thus, when using the analytical method to estimate sediment yield from a single subwatershed, if the sediment supply from the planes is in excess of the channel transport capacity, it is assumed that this excess is immediately deposited. In the numerical method, a more realistic view of the deposition process is used. If the sediment being transported (i.e., in suspension) exceeds the transport capacity, the sediment routing scheme will predict aggradation (the suspended sediment in excess of the transport capacity) as compared with the feasible aggradation given the flow conditions and the settling velocity of the sediment particles to determine the sediment deposited at each time step. This type of consideration is quite realistic in the routing of fine materials because they will probably not settle out in relatively short reaches of a channel even if the transport capacity is much smaller than the sediment supply.

Armoring of the bed is the natural equilibrium of the bed reach, after the fine material is transported away by the flow, resulting in the exposure of a thin layer of coarser particles at the bed surface.[21] This layer of coarser particles is much more difficult for the flow to move, and thus, it protects the finer sediment below from erosion, hence, the name armoring. The numerical routing method accounts for this process as it considers the depth of loose soil and the sediment size distribution within

[21] D. B. Simons and F. Senturk, *Sediment Transport Technology* (Water Resources Publications, Fort Collins, Colorado, 1976), p 506.

the loose soil layer. The analytical method, however, estimates sediment yield solely as a function of transport capacity, and only by an unrealistic decrease in channel detachment coefficient can the analytical method be brought into agreement with the numerical method.

The numerical method of the third component of MULTSED is more realistic than the analytical method of the first component. Thus, a question arises as to whether, for calibration purposes, the watershed(s) should be modeled as two planes whose output is generated by component 1 flowing into a channel using component 3 to route the flow, or simply as a single subwatershed using only component 1. For the small watersheds considered here (all less than 16 acres) with heavily vegetated, simple swale channels, the armoring and natural suspended sediment settling processes are not significant since erosion from heavily vegetated channels is negligible and the flow velocity for wide, shallow, heavily vegetated swale channels is low enough that most of the excess supply will settle out (this has been confirmed by some test runs for these watersheds using both modeling approaches). Assuming that the approximations in the analytical method are fairly reasonable for the watersheds considered here, component 1 was used for the calibration.

Optimization Technique

The generalized reduced gradient (GRG) algorithm[22] was chosen to perform the formal minimization of the sum of squares difference between the measured and simulated hydrographs because it has two important advantages over other optimization techniques. First, it is a very efficient and powerful nonlinear optimization algorithm which converges to the "optimal" solution quite rapidly. Second, it is the only nonlinear optimization algorithm which allows bounds to be placed on the parameters. In previous attempts to develop objective approaches to evaluate and/or calibrate hydrologic models it was necessary to introduce a certain amount of subjectivity as hydrologists changed the optimization code in order to keep parameters within their physically meaningful ranges.[23] However, when using GRG, physically meaningful bounds may be placed on the parameters and considered directly in the optimization. Hence, the hydrologic "best fit" simulation based on physically reasonable parameters is obtained totally objectively from GRG. However, it should be remembered that in the procedure reported here, the final calibration is generally not determined totally objectively because of the adjustments required to obtain the appropriate sediment transport capacities.

It should be noted that GRG is a nonlinear optimization code and as such it requires an assumed starting point, and theoretically the quality of the resulting solution (i.e., whether a local optimum or the global optimum is obtained) is a function of the starting point. The sum of squares surface for the difference function between the measured and simulated hydrographs appears to be unimodal (i.e., there are no local optimums). Therefore, GRG tends to converge to the same general solution regardless of the starting point. However, the speed of the convergence is a function of the starting point and so it must be chosen intelligently to reduce computer costs.

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[22] J. Abadie and J. Carpentier, "Generalization of the Wolfe Reduced Gradient Method to the Case of Nonlinear Constraints," *Optimization*, R. Fletcher (Ed.) (Academic Press, London, 1969).

[23] D. R. Dawdy and T. O'Donnell, "Mathematical Models of Catchment Behavior," *Journal of the Hydraulics Division*, ASCE, Vol 91, No. HY4 (1965), pp 123-137.

For this work, the GRG code developed by Lasdon et al.,[24] as modified for use in the OPT System at the University of Illinois, was used. To efficiently use component 1 of MULTSED (MSED1) in conjunction with GRG to optimize the hydrograph fit, the entire sediment yield portion of MSED1 was deleted. The remaining hydrologic portion of MSED1 was then set up as a series of subroutines within the collection of subroutines called by GRG. The hydrologic portion of MSED1 is called by the objective function subroutine, which calculates the sum of squares difference between the measured (input) and simulated (by the hydrologic portion of MSED1) hydrographs. GRG calculates the reduced gradient of the objective function in the vicinity of the current point. From the reduced gradient, GRG determines the direction of greatest improvement of the objective function. GRG then performs a one-dimensional search in this direction and steps to the best point. When the objective function reduced gradient is within a prespecified tolerance of zero, a local optimum (in this case, probably the global optimum) has been found and GRG terminates. Thus, for each GRG iteration, the objective function value must be calculated up to seven times to determine the reduced gradient. Fortunately, GRG converges to the optimal solution rather quickly and the computational time is not excessive.

Initial Hydrograph Response Time

The optimal resistance coefficient values for the hydrologic "best fit" were generally too large to allow sufficient flow velocity for the calculated sediment transport capacities to be large enough to reproduce the measured sediment yield. Such high resistance becomes necessary to reproduce the measured response time between the rainfall hyetograph and the initial rise of the runoff hydrograph. This is primarily due to the kinematic wave routing approach's inability to account for the natural attenuation (i.e., backwater *effects*), *which* occurs in the actual runoff process. Thus, in the kinematic wave approximation, the timing of the simulated hydrograph is only a function of the overland and channel flow velocities. To artificially account for natural attenuation, kinematic wave routing schemes must decrease the flow velocities by increasing the overland and channel flow resistance coefficients. While this deviation from reality has provided very reasonable and acceptable results for modeling overland flow,[25] it clearly causes problems when modeling sediment yield where higher, more realistic flow velocities are needed to obtain reasonable sediment detachment and sediment transport capacities.

The process of shifting the measured hydrograph to begin earlier serves to remove the effects of natural attenuation in the data. Thus, when fitting the model to the shifted data, the kinematic wave routing approximation is being used to model data which somewhat corresponds to the "no backwater effects" assumption.

From a practical hydrologic viewpoint, the justification for using a time shift on the data is twofold. First, when calibrating runoff events on small watersheds, hydrologists are generally most concerned with reproducing the peak, volume, and general shape of the measured hydrograph. Reproducing the measured time lag between the hyetograph and hydrograph is of secondary importance. This is partially due to the quality of the rainfall data. Generally, rainfall data are obtained by continuously

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[24] L. S. Lasdon, A. D. Waren, M. W. Ratner, and A. D. Jain, "GRG User's Guide," *Technical Memorandum CIS-75-02* (Department of Operations Research, Case Western Reserve University, November 1975).

[25] D. A. Woolhiser.

recording rain gages. The hyetograph is then defined by identifying break points on the mass rainfall curve. This process introduces error in determining the break points and the proper intensity occurring at any given time in the storm. Furthermore, there is also the standard question of whether the rainfall at the rain gage is representative of the true areal and temporal rainfall distribution over the entire watershed. Second, from a watershed management standpoint, generally the most important aspects of a model are its ability to reproduce the peak, volume, and shape of the measured hydrograph and the measured sediment yield, rather than the timing with respect to rainfall.

To perform the time shift, two modifications were proposed and included in the calibration subroutines. One modification allows the measured hydrograph to be shifted a prespecified number of minutes, and then the "shifted" hydrograph is fitted. The other modification matches the peak flow times of the measured and simulated hydrographs and then the sum of squares difference between the "shifted" simulated hydrograph and the measured hydrograph is minimized. By using either of these options, the optimization centers around the hydrologic abstractions and their corresponding parameters, while the resistance coefficients remain fairly close to their initial values with only small changes to improve the shape of the simulated hydrograph. Thus, hydrologic calibration can be performed with the resistance coefficients kept in the range of values which allow duplication of the measured sediment yields.

Suggested Calibration Procedure

The calibration procedure described below was developed based on the experience gained while calibrating the runoff and sediment yield parameters for MSED1 for 17 storm events on 5 small midwestern watersheds. The general principles and basic concepts described below were used in calibrating all 17 storm events, while the specific procedure outlined was used on only the last 7 storm events calibrated (i.e., the storms on the modified Lawson Creek Tributary number 1 watersheds). The proposed procedure proved to be quite efficient when calibrating these seven storm events.

Step 1: Estimating the Initial Time Shift

Two modifications of the calibration subroutines were developed to perform time shifts on the data: one which shifted the data a prespecific number of minutes and one which matched peak discharge times and then calculated the sum of squares difference. The modification which shifts the data a prespecified number of minutes seemed to be the more practical and reasonable method to use. However, this method requires an appropriate estimate of the initial time shift. Such an estimate may be obtained by one of the following three methods.

1. If previous calibration experience is available, choose a set of optimal parameter values from a previous calibration, which was under conditions similar to the storm event being calibrated. Perform a simulation using MSED* with the chosen parameter values and the input data for the storm event to be calibrated. Compare the peak discharge, total runoff volume, and overland and channel sediment transport capacities** of the simulation with the measured values. If the transport capacities

*Actually, MSED1 should be modified so that the overland flow transport capacity is output because the overland areas are the primary erosion sources for small watersheds (see Step 3).

**By setting the detachment coefficient values to their upper bounds, the total sediment yield will equal the channel sediment transport capacity.

exceed the measured sediment yield, and the peak discharge and total runoff volume are reasonably close to the measured values (generally this should not be a concern unless the difference is very large), the time difference between the measured and simulated peak discharges should be used as the time shift. Otherwise, the overland and channel flow resistance parameters (ADW and n, respectively) should be reduced until the sediment transport capacities exceed the measured sediment yield. Then the measured and simulated hydrographs should be compared to determine the appropriate time shift.

2. If no previous calibration experience is available for this watershed, choose calibrated parameter values for a similar storm on a similar watershed. Perform a simulation using MSED1 with the chosen parameter values and the input data for the storm event to be calibrated, and use the guidelines for comparison discussed in Method 1 to determine the time shift.

3. If no previous calibration experience on this watershed or any similar watershed is available, choose the resaturated hydraulic conductivity, KH, from the lower portion of the physically reasonable range; the overland flow resistance coefficient, ADW, Manning's n, and the potential ground and canopy cover interception volumes, VG and VC, respectively, from the upper portion of the range; and the average capillary suction, $-\psi$, from the middle of the range. Perform a simulation using MSED1 with the chosen parameter values and the input data for the storm event to be calibrated, and use the guidelines for comparison discussed in Method 1 to determine the time shift.

Methods 1 and 2 should provide a good estimate of the proper time shift because the calibration experience gained in this study showed that the calibrated parameter values for the various storm events tended to remain fairly constant for a specific watershed and were consistent when comparing similar watersheds. Method 3 should provide a good estimate of the proper time shift because the calibration results indicated that the portion of the physically reasonable parameter range identified in Method 3 tended to contain the "optimal" parameter value for each of the unknown parameters.

As a final note, for those cases where there is no distinct measured peak discharge but rather a broad flat hydrograph peak, the proper time shift should be determined by plotting both the measured and the simulated hydrographs and comparing the peak regions rather than just the single peak discharge.

Step 2: Formal Calibration and Adjustments

Having determined the proper time shift, the formal calibration of the hydrograph is done using GRG. The parameter values used in Step 1 to determine the proper time shift make good initial values for the calibration using GRG. Perform a simulation using MSED1 and the calibrated parameters.

If the sediment transport capacities exceed the measured sediment yield, the hydrologic "best fit" which allows the appropriate sediment yield has been found and Step 3 should be performed.

If the sediment transport capacities are less than the measured yield, reduce the values of n and/or ADW until the sediment transport capacities exceed the measured sediment yield. Not only is the sum of squares surface of the difference between the measured and simulated hydrographs unimodal, but it is also fairly flat in the optimal region in the n and ADW directions. That is, the quality of the hydrologic fit is fairly insensitive to changes in n and ADW from their calibrated values. Thus, after reducing n and/or ADW, check the quality of the hydrologic fit in terms of peak discharge, total

runoff volume, and the sum of square difference. It is likely that the quality of the hydrologic fit will still be good. If so, go to Step 3 without further calibration. If, on the other hand, the quality of the hydrologic fit is no longer acceptable, change the time shift to its new value (if necessary) and set the upper bounds on n and ADW to those values necessary to obtain the measured sediment yield.

This calibration procedure should be repeated until a reasonable hydrologic fit is obtained which allows the measured sediment yield to be simulated.

Step 3: Calibration of Detachment Coefficients

Having obtained a "good" hydrologic fit, which has sufficiently large overland and channel sediment transport capacities to reproduce the measured sediment yield, the detachment coefficients may be determined by iteration such that the simulated total sediment yield from MSED1 closely matches the measured yield. Intuitively, it might be expected that a wide variety of combinations of the three detachment coefficients would produce the measured sediment yield; thus, the usefulness of calibration would seem to be reduced because a range of values is the best that can be identified. However, due to the structure of the model and physical considerations, the overland flow and channel flow detachment coefficients may be viewed as insignificant compared to the raindrop splash detachment coefficient.

In the calibration of the detachment coefficient values, sediment yield was generally not sensitive to the overland flow detachment coefficient (i.e., in 11 of the 17 cases studied). This does not mean that overland flow detachment is unimportant in the true physical sense, but rather the insensitivity is due to the structure of the model. Recall that the total available sediment supply, Va, is estimated in MULTSED as

$$V_a = V_r + V_f \qquad \text{[Eq 14]}$$

where V_r = nonporous volume of material detached by raindrop splash; and V_f = nonporous volume of material detached by overland flow.

In MULTSED, Vr is estimated as

$$V_r = a_1 A(1 - \eta)A_b \; i^2 \qquad \text{[Eq 15]}$$

where a_1 = an empirically determined constant describing the erodibility of the soil; η = soil porosity; A_b = area reduction factor (i.e., the fraction of bare or unprotected soil in the area); i = rainfall intensity; and A = total surface area subjected to rainfall.

V_f is estimated as

$$\begin{aligned} V_f &= D_f\,(V_t - V_r) && \text{if } V_t \geq V_r \\ V_f &= 0 && \text{if } V_t < V_r \end{aligned} \qquad \text{[Eq 16]}$$

where V_t = the sediment transport capacity of the overland flow (sum for all sediment sizes); and D_f = the overland flow detachment coefficient. The total supply is then

distributed by size fractions based on the particle size distribution, and the supply for a given size is then compared to the transport capacity for that size. The fraction of the total transport capacity represented by a given size may not be the same as the fraction of the available sediment represented by that size. Generally, V_r must be greater than the total transport capacity in order for sufficient sediment supply to be available, and hence, D_f becomes unimportant.

From a physical standpoint, the primary sources of erosion for the watersheds of interest to Army land managers will be the overland flow areas. This is especially true for the watersheds examined in this report. Each of these watersheds is small with highly vegetated, swale channels (especially the Lawson Creek Tributary number 1 channel which is completely grassed throughout its entire length). Therefore, from a physical standpoint, little channel erosion would be expecteed. The value of the channel detachment coefficient was assumed to be unimportant and set equal to zero.

In most cases, the raindrop splash detachment coefficient, a1, is the primary erosion controlling parameter requiring calibration. However, for those training sites where gullies are a problem (e.g., Fort Knox), both the raindrop splash and channel flow detachment coefficients need to be examined. A good way to separate the effects of the two sources of sediment might be to use reasonable values of a1 obtained from calibration of other similar watersheds and then to iterate on the channel flow detachment coefficient until the excess measured sediment is accounted for. (Note: calibration experience described in Chapter 6 shows that detachment coefficient values are transferable between similar watersheds.)

Documentation of Calibration Algorithm

A description of the calibration program, including a listing of the GRG and model subroutines and example data files, is presented by Melching and Wenzel.[26]

[26]C. S. Melching and H. G. Wenzel, Jr., "Calibration Procedure and Improvements in MULTSED," *Appendix A, Civil Engineering Studies, Hydraulic Engineering Series No. 38* (University of Illinois, July 1985).

6 CALIBRATION EXPERIENCE

Description of Watersheds Used for Calibration

Runoff and sediment yield data for 17 storm events on 5 small watersheds, 2 in Iowa and 3 in Illinois, were used for calibration. Actually, the two watersheds in Iowa are adjacent, while the three in Illinois are permutations of the same basic watershed.

Lawson Creek Tributary No. 1

This watershed comprises the northwest portion of the Sheffield, Illinois low-level radioactive waste disposal facility. This facility is located 3 miles southwest of Sheffield, Illinois, and its geological and hydrologic characteristics have been studied by the U.S. Geological Survey (USGS) since 1975.[27] Monitoring of water and sediment yield began in July, 1982. From July 1982, to late July 1983, Lawson Creek Tributary number 1 (LCT 1) had an area of 3.25 acres, as denoted by the heavy line in Figure 11. In late July 1983, the drainage pattern was altered such that an additional 1.1 acres drained through LCT 1. The modified watershed is referred to as LCT1P, and its boundary is denoted by the dashed line in Figure 11. Most of the additional 1.1 acres was bare or nearly bare soil, and so the water and sediment yield for LCT1P show significant increases relative to those for LCT 1. To seal off the new sources of high flow and sediment, a berm was built across the west end of the watershed on April 10, 1984. The resulting 2.86 acre watershed is referred to as LCT1P2, and its boundary is denoted by the dotted line in Figure 11.

These permutations on the LCT 1 watershed offer an interesting study in terms of relating detachment coefficients to Army training practices and management practices. LCT1P2 can be viewed as corresponding to the unaltered state of the training site (watershed). LCT 1 has somewhat more bare soil and greater sediment yield than LCT1P2, and may be viewed as the training site (watershed) after limited training activity. LCT1P has a significant area of bare soil and large sediment yields, and may be viewed as the training site (watershed) after extensive training activity.

The soils in this watershed are mainly from the Fayette and Strawn soil associations. The Strawn series soils are deep, strongly sloping to steep, well-drained to moderately well-drained grayish brown silt loams with moderate permeability and moderate available water capacity. The Fayette series soils are gently sloping to very steep, well-drained grayish brown silt loams with moderate permeability and high to very high available water capacity. Based on USDA soil surveys, a reasonable range for the resaturated hydraulic conductivity is 0.1 to 1.0 in./hr. The USGS provided data on the soil porosity (0.45) and the initial soil moisture (from tensiometer data) for each storm event, while the final soil moisture fraction was assumed to be 1.0. Actually, the initial soil moisture fraction, SI, was determined by combining tensiometer data with antecedent rainfall (if any) on the storm date, as shown in Table 10. Data presented by Bouwer[28] indicates a reasonable range of the average capillary suction is -5 to -40 in. for these soils.

[27] J. R. Gray, Personal Communication (Urbana, Illinois, 1984).

[28] H. Bouwer, "Unsaturated Flow in Ground-Water Hydraulics," *Journal of the Hydraulics Division*, ASCE, Vol 90, No. Hy5 (1964), pp 121-144.

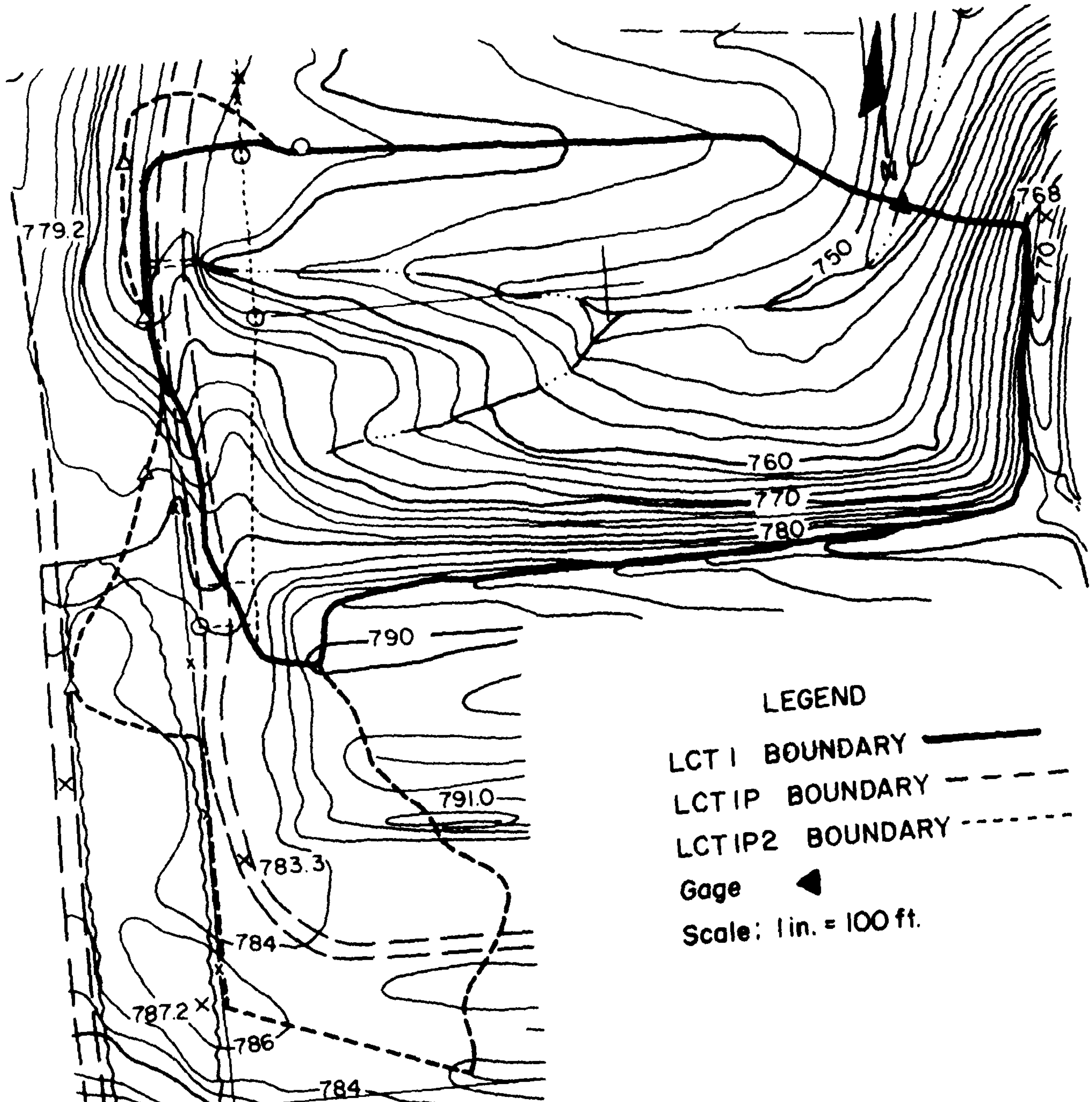

Figure 11. Lawson Creek Tributary number 1 watersheds northwest corner of the Sheffield, Illinois, low-level radioactive waste disposal facility.

Table 10

Initial Soil Moisture Fraction for Lawson Creek Tributary (LCT) Number 1 Watersheds

Watershed	Date	S_1, fr. Tensiometer Data	Antecedent Precipitation	S_1 Used
LCT 1	07/21/82	0.60	--	0.60
LCT 1	11/01/82	0.56	0.73 in.	0.99
LCT 1	06/29/83	0.40	0.31 in.	0.80
LCT1P	07/30/83 (1)	0.51	--	0.51
LCT1P	07/30/83 (2)	0.51	2.17 in.	0.99
LCT1P	08/26/83	0.44	--	0.44
LCT1P	09/18/83	0.51	0.51 in.	0.99
LCT1P2	05/25/84	0.71	0.31 in.	0.90
LCT1P2	06/06/84	0.62	0.12 in.	0.65
LCT1P2	10/31/84	--	0.45 in.	0.99

The watershed is covered with brome grass, which has an interception potential between 0.01 and 0.05 in. For some of the storms which had significant antecedent rainfall (see Table 10), the interception potential was assumed to be nearly filled, and the interception potential range was taken as $0.001 \leq VG \leq 0.002$ in. The percentage of vegetal (ground) cover varies both spatially over the watersheds and between seasons. For the summer of 1982, the left side of LCT 1 (looking upstream) had 85 percent cover and the right side had 60 percent cover, while in the summer of 1983 the cover percentages were 85 and 40 for the left and right sides, respectively. For the summer and fall of 1983, the left side of LCT1P had 70 percent cover and the right side had 35 percent cover. For the summer of 1984, the cover conditions for LCT1P2 returned to those of LCT 1 in the summer of 1983. In the winter, the percentages on each side for each watershed dropped by about 20 percent. Due to a lack of sufficient information on the overland flow resistance coefficient, ADW, it was assumed to be unbounded. The channel is heavily grassed, so a relatively high Manning's n value would be expected. Using Cowan's method,[29] the range for n was estimated to be 0.05 to 0.10.

Complete rainfall, runoff, and sediment yield data are available for the 10 storm events listed in Table 10. The rainfall hyetograph, runoff hydrograph, and total measured sediment yield for each of these storms are presented in Appendix C.

For any given storm event on the watershed, only 8 to 10 sediment concentration points are available. While this is an unusually large amount of good quality sediment concentration data, the estimate of the total measured sediment yield can further be enhanced by using a regression equation developed by Gray.

[29]W. L. Cowan, "Estimating Hydraulic Roughness Coefficients," *Agricultural Engineering*, Vol 37, No. 7 (1956), pp 473-475.

$$Q_{SC_t} = 7942.1\, Q_{mt}^{0.33132} \quad \text{[Eq 17]}$$

where Q_{SC_t} = sediment concentration at time t in mg/l. This equation was derived by performing a regression analysis on the flow and sediment concentration data, and by using it, sediment concentrations corresponding to each point on the hydrograph may be calculated and a better estimate of the total sediment yield may be obtained. This equation has a correlation coefficient of 0.823 which, given the relative accuracy of sediment concentration data, makes it a very reasonable representation of the true sediment concentration and the true sediment load. Equation 17 is only valid for LCT 1 and LCT1P, so the total measured sediment yield for LCT1P2 was determined from the sediment concentration data.

Four Mile Creek Watershed

The Four Mile Creek watershed originates in northwest Tama County, Iowa, near Lincoln. The entire Four Mile Creek basin has been monitored for water, sediment, and nutrient yields by Iowa State University since 1976.[30] In this study, only two small watersheds in the Four Mile Creek basin are examined. These small watersheds are denoted as ISU-1 and ISU-2 (Iowa State University watersheds number 1 and 2).

ISU-1 and ISU-2 are 12.2 and 15.5 acres, respectively, and their topography and soils are shown in Figure 4. The soils of ISU-1 and ISU-2 are Tama silt loam and Colo-Judson silt loam, which are moderately permeable, dark colored soils with gently sloping topography. Based on information provided by Park[31] and Park and Mitchell, the porosity of the composite soil is 0.475 and the reasonable range of values for the resaturated hydraulic conductivity is 0.01 to 0.30 in./hr. The initial soil moisture fraction is taken from the antecedent soil moisture calibrated by Park (see Table 11), and the final soil moisture fraction is assumed to be 1.0. Since these soils are silt loams, the range for the average capillary suction was taken as -5 to -40 in.

Both ISU-1 and ISU-2 are agricultural watersheds which have been used for growing corn (ISU-1 in 1977, ISU-2 in 1978) and soybeans (ISU-1 in 1978, ISU-2 in 1977) on a yearly rotation basis. Each spring the residue from the previous year's crop is plowed and/or disked into the soil along with fertilizer, to provide a food base for the new crop and a small amount of erosion protection for the soil. Complete details on the ground and canopy cover conditions for these watersheds are obtainable from the tillage schedule and crop progress photos presented by Johnson.[32] Once again, the overland flow resistance coefficient was unbounded in the calibration procedure. For these watersheds, the channel is less vegetated than Lawson Creek tributary number 1, and so from Cowan's method, the n values range from 0.03 to 0.10.

Table 11 lists the dates of the storm events which were calibrated for this report. The storm events are not the same for the adjacent watersheds because it was found that the runoff when soybeans are planted is far less than when corn is planted. Thus, storms which produced significant runoff (peak discharge > 2 cfs [cubic feet per second]) on the watershed planted with corn often produced insignificant runoff (peak discharge < 0.6

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[30] H. P. Johnson, 1976-77; H. P. Johnson, 1977-78.

[31] S. W. Park, *Modeling Soil Erosion and Sedimentation on Small Agricultural Watersheds*, Ph.D. Thesis (Department of Agricultural Engineering, University of Illinois, 1981).

[32] H. P. Johnson, 1977-78.

Table 11

Initial Soil Moisture Fraction for ISU-1 and ISU-2

Watershed	Date	S_I
ISU-1	04/19/77	0.81
ISU-1	08/15/77	0.81
ISU-1	05/27/78	0.44
ISU-2	08/15/77	0.60
ISU-2	04/18/78	0.83
ISU-2	05/27/78	0.79
ISU-2	05/31/78	0.80

cfs) on the neighboring watershed planted with soybeans. When soybeans are planted, a large amount of residue from the previous year's corn crop is tilled into the soil. However, when corn is planted, a very small amount of residue from the previous year's soybean crop is tilled into the soil. Thus, when soybeans are planted, the surface roughness is much greater and the detention storage is much greater than when corn is planted. Furthermore, the litter from the previous year's corn crop also protects the soil surface from the detrimental effects of raindrop impact, thereby preserving a high initial infiltration capacity. This increased detention storage and high infiltration capacity probably accounts for the difference in runoff magnitude.

Complete rainfall, runoff, and sediment concentration data are available for the seven storm events on ISU-1 and ISU-2 listed in Table 11. The rainfall hyetograph, runoff hydrograph, and total measured sediment yield for each of these storms are presented in Appendix C. For these watersheds, the total sediment yield was estimated from sediment concentration data.

Calibration Results

Hydrologic Fitting

Thirteen of the seventeen storm events calibrated required some time shifting of the hydrographs and/or extra constraints on the resistance coefficients to achieve a hydrologic fit which allows the proper sediment yield. Nevertheless, despite the reduction of hydrologic fit quality brought on by the hydrograph shifting and resistance coefficient constraints, the hydrologic fits obtained were good. This is shown in Table 12 where the percent difference between the measured and calibrated hydrographs in terms of the peak discharge and the total runoff volume is given. Also in Table 12, the final calibration objective function is given as a percentage of the total sum of squares of the flow data as computed using Equation 18. This gives some idea of the quality of fit in terms of the hydrograph shape.

$$TSS = \frac{\sum_t (Q_{mt} - Q_{st})^2}{\sum_t Q_{mt}^2} \qquad \text{[Eq 18]}$$

The "best fit" hydrograph for each of these storm events is plotted with the measured hydrograph for comparison in Appendix C.

Table 12

Quality of the Hydrograph Fit

Watershed	Date	Percent Difference* (Measured Versus Calibrated) Peak	Volume	TSS
LCT 1	07/21/82	- 9.7	- 2.4	1.8
LCT 1	11/01/82	+ 4.2	- 7.8	2.4
LCT 1	06/29/83	+ 7.1	- 8.0	2.8
LCT1P	07/30/83 (1)	+17.8	- 7.0	2.4
LCT1P	07/30/83 (2)	+22.3	- 6.8	7.0
LCT1P	08/26/83	+33.5	-12.9	6.0
LCT1P	09/18/83	- 7.9	- 5.3	2.1
LCT1P2	05/25/84	+ 8.9	- 5.8	2.2
LCT1P2	06/06/84	+16.0	- 5.8	3.6
LCT1P2	10/31/84	- 1.3	-13.9	2.1
ISU-1	04/19/77	-16.3	+ 3.4	8.0
ISU-1	08/15/77	+ 2.5	-13.5	6.9
ISU-1	05/27/78	-27.0	- 6.3	11.9
ISU-2	08/15/77	-11.7	- 0.2	2.5
ISU-2	04/18/78	+19.3	- 0.7	1.3
ISU-2	05/27/78	- 5.7	-12.1	3.7
ISU-2	05/31/78	-20.5	+13.4	5.7

*Percent Difference = [(simulated-measured)/measured] x 100.

The quality of the hydrologic fit could be improved even further by making the adjustment in MULTSED that doesn't allowing infiltration after the rainfall input has ceased. Ward[33] reports that this adjustment has already been made with great success in the MULTSED version at New Mexico State University.

Furthermore, it is clear from the comparison of measured and simulated hydrographs in Appendix C that the simulated recession curves decrease much too rapidly, and so this adjustment would improve the fits obtained in this study. An adjustment of this type is not uncommon in hydrologic modeling, and it can be interpreted as accounting for the effects of prompt subsurface flow (i.e., interflow) on the measured hydrograph. This adjustment was not made in the calibration work performed here. Nevertheless, it is felt that the raindrop splash detachment coefficient values calibrated here are quite reasonable since the majority of sediment detachment and transport occurs before the hydrograph reaches the lower part of the recession curve.

[33]T. J. Ward, Personal Communication (Champaign, Illinois, 1984).

Table 13 shows the calibrated values of the hydrologic parameters. All of these values fall within the reasonable range for each respective parameter. The variance in parameter values from storm to storm is not excessive. Furthermore, a comparison between the similar watersheds (i.e., LCT 1, LCT1P, and LCT1P2; and ISU-1 and ISU-2) shows good consistency in the values of all the parameters. These results indicate that this model can generate realistic runoff events given adequate data about the site conditions. This performance is expected from a good physically based hydrologic model. Finally, the results given in Table 13 support the following important points:

1. Since the parameter values for MULTSED show good consistency between similar watersheds, it is concluded that calibrated hydrologic information for one watershed may be transferred for simulation of similar ungaged watersheds.

2. The calibrated parameter values tended to fall into certain portions of their physically reasonable ranges (i.e., KH in the lower portion, ADW, n, and interception potential in the upper portion, and $-\psi$ in the middle portion). Thus, for ungaged watersheds for which there are no similar watersheds for parameter transfer, reasonable simulation results may be obtained choosing parameter values in the appropriate portions of the physically reasonable ranges.

3. The fact that n and ADW tended to be in the upper portion of their physically realistic ranges is as expected because these higher resistance values help the kinematic wave approximation artificially simulate natural attenuation of the flow. Because values within the physically reasonable ranges of n and ADW are capable of accounting for natural attenuation (with some time shifting), it is reasonable that the kinematic wave approximation is acceptable for erosion modeling on small watersheds.

Detachment Coefficient Calibration

As pointed out in Chapter 5, the overland flow detachment coefficient is insignificant due to the structure of the MULTSED model, and for the heavily vegetated swale channels found in these watersheds, it is reasonable to assume the channel erosion and, hence, the channel detachment coefficient, is negligible. Thus, in this study, only the raindrop splash detachment coefficient, a_I, was calibrated. The optimal values of a_I, and the measured and simulated sediment yield for each storm event are shown in Table 14. These agree quite well with those found by Ward and Seiger[34] for rainfall simulator tests on five different soil types in the Pinon Canyon watershed in Colorado. Ward and Seiger found the mean values of a_I for these soils ranged from 0.00047 to 0.02433.

By observing the results reported in Table 14, two important inferences may be made:

1. The rainfall detachment coefficients for ISU-1 and ISU-2 seem to be fairly consistent (especially comparing the August 15, 1977 storm event). This leads to the conclusion that these a_I values may be transferable between similar watersheds for similar storm conditions.

2. It is also clear that LCT1P and LCT 1 generally have higher rainfall detachment coefficient values than LCT1P2, with the mean value for LCT1P (the worst case) more than an order of magnitude greater than that for LCT1P2 (the natural case). This

[34] T. J. Ward and A. D. Seiger, *Infiltration Tests at Pinyon Canyon, Completion Report* (Engineering Research Center, New Mexico State University, September 1983).

Table 13

Calibrated Hydrologic Parameter Values*

Watershed	Date	KH (in./hr)	$-\psi$ (in.)	VG (in.)	VC (in.)	n	ADW
LCT 1	07/21/82	0.100	5.0	0.010	--	0.090	512
LCT 1	11/01/82	0.100	20.4	0.050	--	0.091	9000
LCT 1	06/29/83	0.107	40.0	0.020	--	0.053	1700
LCT1P	07/30/83 (1)	0.100	16.7	0.050	--	0.061	2300
LCT1P	07/30/83 (2)	0.100	20.0	0.001	--	0.081	1817
LCT1P	08/26/83	0.100	20.4	0.050	--	0.086	1900
LCT1P	09/18/83	0.100	5.0	0.001	--	0.050	2200
LCT1P2	05/25/84	0.100	16.4	0.001	--	0.100	5363
LCT1P2	06/06/84	0.118	19.8	0.050	--	0.097	10000
LCT1P2	10/31/84	0.108	25.0	0.002	--	0.050	60000
ISU-1	04/19/77	0.183	30.0	0.020	--	0.061	17000
ISU-1	08/15/77	0.170	30.0	0.000	0.050	0.100	13190
ISU-1	05/27/78	0.202	29.8	0.020	0.060	0.067	31270
ISU-2	08/15/77	0.245	32.2	0.020	0.06	0.047	1275
ISU-2	04/18/78	0.031	36.3	0.020	--	0.100	33078
ISU-2	05/27/78	0.145	30.0	0.020	0.06	0.080	49711
ISU-2	05/31/78	0.218	29.9	0.000	0.02	0.035	10795

*KH = resaturated hydraulic conductivity.
$-\psi$ = average capillary suction (expressed as a positive value).
VG = ground cover interception.
VC = canopy cover interception.
n = Manning's n for channel flow.
ADW = the maximum overland flow resistance parameter.

Table 14

Calibrated Values of the Raindrop Splash Detachment Coefficient

Watershed	Date	a_1	Sediment Yield: Measured (lb)	Sediment Yield: Simulated (lb)
LCT 1	07/21/82	0.0140	2190	2190
LCT 1	11/01/82	0.0037	2180	2180
LCT 1	06/29/83	0.0088	3830	3840
LCT1P	07/30/83 (1)	0.0107	13960	13950
LCT1P	07/30/83 (2)	0.0114	9970	10000
LCT1P	08/26/83	0.0057	11520	11570
LCT1P	09/18/83	0.0230	8510	8510
LCT1P2	05/25/84	0.0013	512	520
LCT1P2	06/06/84	0.0004	180	180
LCT1P2	10/31/84	0.0007	35	35
ISU-1	04/19/77	0.0088	33120	31510
ISU-1	08/15/77	0.0198	8550	8540
ISU-1	05/27/78	0.0007	3490	3480
ISU-2	08/15/77	0.0196	2280	2270
ISU-2	04/18/78	0.0010	1270	1230
ISU-2	05/27/78	0.0027	25000	24900
ISU-2	05/31/78	0.0009	1940	2010

comparison points qualitatively toward the type of changes which will need to be made in the values of this coefficient to reflect the watershed degradation caused by training, in addition to adjusting the cover percentages.

The results of 17 calibration trials are hardly conclusive, and therefore, further calibration and rainfall simulator tests are desirable. The calibration procedure described in this report should serve as a good guide to further calibration efforts. Furthermore, the results of these example calibrations should provide a useful foundation for training area modeling until more calibration information and rainfall simulator test results become available.

Overland Flow Resistance

The results of these 17 storm calibrations provide little insight into selecting a value of the overland flow resistance coefficient, ADW, because its value was found to vary greatly between the storms and between the watersheds. Actually, ADW is the maximum overland flow resistance value which would occur if 100 percent ground cover existed over the watershed. In MULTSED, the actual overland flow resistance coefficient, K_g, is estimated as

$$K_g = 100 + (ADW - 100)C_g^2$$

where Cg = the ground cover fraction.

By considering K_g instead of ADW, a better idea of how to determine the proper overland resistance value can be obtained. Table 15 shows the K_g values for each of the calibrated events. In general, the Army goal of modeling of training sites is to examine the increase in runoff and sediment yield caused by training activities. Thus, if the results for LCT1P2 (whose events produce small sediment yields) are ignored, it is clear that the variance in K_g values is much smaller than that for ADW. Based on Table 15, it seems that when modeling post-training activity conditions, a good initial choice of ADW should be one that results in K_g being between 400 and 1000. Furthermore, LCT1P2 is similar to natural state training area conditions, and from this it appears that value of K_g greater than 2500 is appropriate. These are reasonable "rules of thumb" for now, but more research regarding the proper choice of ADW, both for the post-training activity and the natural state watershed conditions, is needed.

Efficiency of the Calibration Program

In the course of calibrating 17 storm events on 5 watersheds for water and sediment yields, the GRG based hydrograph calibration program was used 66 times. The number of objective function evaluations (i.e., hydrograph simulations) necessary to obtain the "optimal" fit, ranged from 46 to 292 for these calibration runs with a mean of 129 and a standard deviation of 55. The primary reason for the variance in the number of objective function evaluations is the selection of the starting point for GRG. For comparison, Ibbitt[35] used a version of Rosenbrock's optimization method,[36] modified to

[35] R. P. Ibbitt, "Effects of Random Data Errors on the Parameter Values for a Conceptual Model," *Water Resources Research*, Vol 8, No. 1 (1972), pp 70-78.

[36] H. H. Rosenbrock, "An Automatic Method of Finding the Greatest or Least Value of a Function," *The Computer Journal*, Vol 3 (1960), pp 175-184.

Table 15

Calibrated Values of the Overland Flow Resistance Parameter

Watershed	Date	K_g
LCT 1	07/21/82	350
LCT 1	11/01/82	3078
LCT 1	06/29/83	932
LCT1P	07/30/83 (1)	947
LCT1P	07/30/83 (2)	761
LCT1P	08/26/83	793
LCT1P	09/18/83	908
LCT1P2	05/25/84	2832
LCT1P2	06/06/84	5240
LCT1P2	10/31/84	31200
ISU-1	04/19/77	269
ISU-1	08/15/77	624
ISU-1	05/27/78	412
ISU-2	08/15/77	146
ISU-2	04/18/78	429
ISU-2	05/27/78	596
ISU-2	05/31/78	207

handle the peculiar fitting problems associated with conceptual catchment models, to fit a simple nine parameter multiple reservoir model (i.e., surface channel, soil moisture, and groundwater storage reservoirs) to synthetic data generated by this same model and then slightly altered. Ibbitt reports that a satisfactory fit was usually achieved in the first few thousand objective function evaluations. While the GRG-based calibration only works with a six-parameter model as opposed to a nine-parameter model, it is doubtful that the additional three parameters would cause an order of magnitude difference in the number of objective function evaluations needed by GRG. Hence, from this comparison it is clear that the GRG-based hydrograph calibration is indeed relatively efficient.

In terms of computer time, all these calibrations were done using the CDC Cyber 175 at the University of Illinois at Urbana-Champaign. For the 66 calibration runs, the execution time ranged from approximately 12 to 130 CP seconds of execution time with a mean of 57 CP seconds and a standard deviation of 33 CP seconds. The execution time for the hydrograph calibration program is primarily a function of the number of objective function evaluations required, and of the number of points on the simulated hydrograph. For example, a calibration requiring simulation of a hydrograph 50 minutes in duration using 233 objective function evaluations, required 68 CP seconds, while a calibration requiring simulation of a hydrograph 120 minutes in duration using 76 objective function evaluations also required 68 CP seconds. Figure 12 shows the general nature of the increase in computer time with the number of objective function evaluations and the number of points on the simulated hydrograph. Based on Figure 12, when calibrating

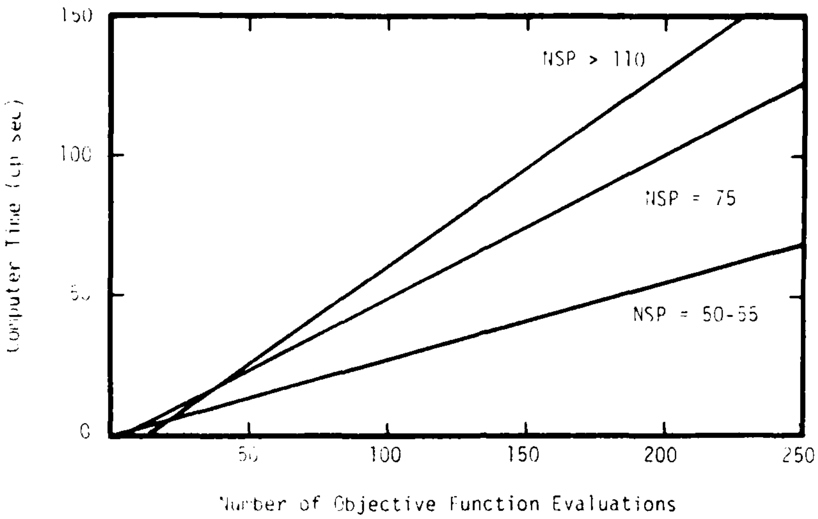

Figure 12. Calibration program computer time as a function of the number of objective function evaluations and the number of points generated for the simulated hydrograph, NSP.

events with long hydrograph durations, it would be best to use flow data at 2 minute intervals, or greater, even when 1 minute data are available, to save computer time.

MULTSED Parameter Transferability

Physically based models represent the system being modeled by decomposing it into its respective components. These components are modeled using appropriate theoretical and/or empirical relations, which use parameters such as hydraulic conductivity, porosity, capillary suction, and flow resistance coefficients, that have physical significance to the field situation. In contrast, regression models and "black box" (input/output) models typically use parameters which are not derivable from the physical conditions of the watershed but rather require extensive calibration to be applicable to any particular watershed. Furthermore, these calibrated parameters are only applicable to that watershed in its current condition (i.e., calibration condition). Therefore, the greatest advantage of physically based models is that the component relations are applicable to a wide range of watershed, conditions without extensive parameter calibration. Physically based models are very flexible and may be applied to any watershed using parameter values derived from data on the soil and vegetation conditions of the watershed, or parameter values transferred from calibration studies of similar watersheds. The vast majority of watersheds do not have runoff and/or sediment yield (especially sediment yield) data available. Therefore, the flexibility and parameter transferability characteristics of physically based models make them an invaluable tool to hydrologists and watershed managers.

The flexibility of physical' based hydrologic models and the transferability of parameter values between similar watersheds for these models is well documented and generally accepted. The results of the hydrograph calibration in this study have pointed to the MULTSED hydrologic parameter transferability in that these parameter values remain consistent when comparing calibrated values between similar watersheds.

Furthermore, Li et al.[37] demonstrated the accuracy, flexibility, and parameter transferability for the hydrologic portion of MULTSED. Li et al. calibrated parameter values for storm events on ISU-1,[38] and then modeled the same storm events over the entire Four Mile Creek basin, achieving good results by transferring the calibrated parameter information for use in modeling appropriate parts of the basin.

The flexibility and parameter transferability of the erosion components of physically based overland erosion models is not as easily shown because, as explained earlier, the overland erosion process is so complex that an adequate relation based on physical principles has not been derived. The results of the calibration work performed here seems to point to the conclusion that detachment coefficients are also transferable between similar watersheds because the detachment coefficients also remain consistent when comparing calibrated values between similar watersheds. Thus, in the following paragraphs, the detachment coefficient transferability for MULTSED will be investigated by simulating sediment yield for a larger midwestern watershed by transferring some of the calibration results found earlier.

Watershed for Parameter Transfer Test

The Highland Silver Lake drainage basin is located approximately 30 miles east of St. Louis near Highland, Illinois. This watershed has been monitored by the Illinois State Water Survey for water and sediment yield since 1981. Figure 13 shows a 3188 acre portion of this basin, called HSL-3, which was used as the watershed for parameter transfer. HSL-3 is comprised of two subwatersheds (HSL-1 and HSL-2 in Chapter 4) whose channels merge to form a larger channel. This main channel continues downstream draining two large planes until it reaches Illinois State Water Survey gaging station number 3 as shown in Figure 13. Subwatershed number 1 (HSL-1) in Figure 13 also serves as a gaged field site (FS5), and so separate soil and vegetation (and/or land use) data are available for HSL-1 and the rest of HSL-3.

The soils in HSL-3 are mainly silt loams and silty clay loams. Four soil types--Cowden, Darmstadt, Herrick, and Huey--account for 84.3 percent of HSL-1 and 82.1 percent of the remainder of the watershed as shown in Table 16. Cowden series soils are deep, poorly drained, nearly level, dark gray silt loams with low permeability and high available water capacity. Darmstadt series soils are somewhat poorly drained, nearly level to sloping, brownish gray silt loams with low to very low permeability and low available water capacity. Herrick series soils are deep, somewhat poorly drained, nearly level, very dark gray silt loams with moderately low permeability and high available water capacity. Huey series soils are poorly drained, nearly level, gray silt loams and silty clay loams with very low permeability and moderate to low available water capacity.

Table 16 also shows the ranges of resaturated hydraulic conductivity, KH, for the top layer and for the underlying layers for each of these soils. From this information, 0.03 to 0.35 in./hr would be a reasonable range for KH throughout the watershed. The

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[37] R. M. Li, D. B. Simons, and T. J. Ward, *Procedure for Evaluating a Data Collection System*, prepared for Office of Research and Development, U.S. Environmental Protection Agency, Athens, Georgia (Civil Engineering Department, Colorado State University, 1980).

[38] H. P. Johnson, 1976-77; H. P. Johnson, 1977-78.

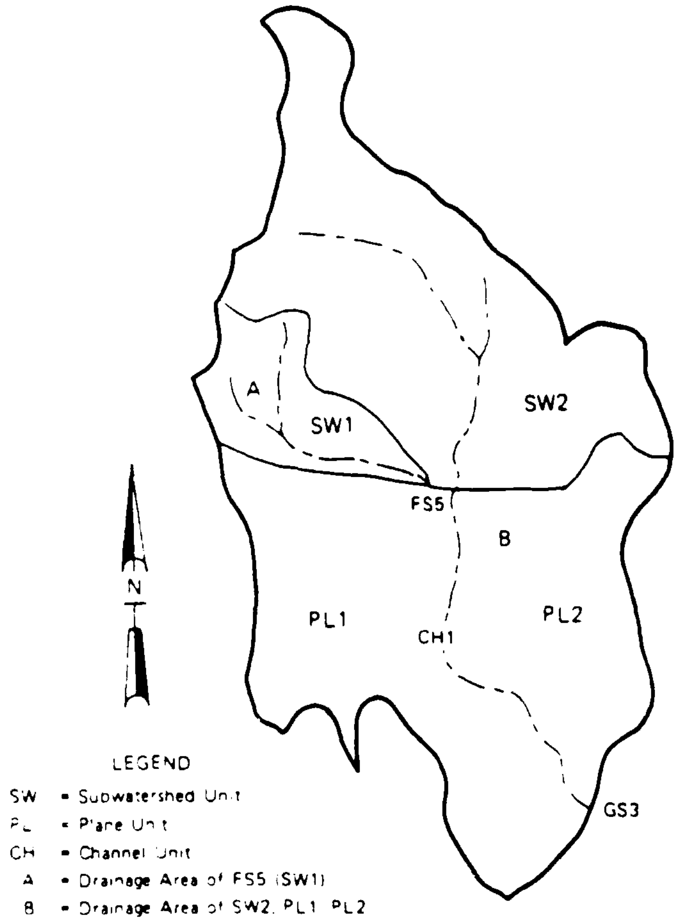

Figure 13. Gaging Station 3 subwatershed of Highland Silver Lake, Highland, Illinois (HSL-3).

Table 16

Highland Silver Lake Watershed: Soil Types and Their Resaturated Hydraulic Conductivities

Soil	HSL-1 (%)	Remainder of HSL-3 (%)	Top Layer, KH (in./hr)	Deep Layers, KH (in./hr)
Cowden	19.0	27.5	0.10-0.32	0.03-0.10
Darmstadt	24.0	27.4	0.03-0.10	< 0.10
Herrick	26.6	14.9	0.32-1.00	0.10-0.32
Huey	14.7	12.3	0.10-0.32	0.03-0.10

final soil moisture fraction was again assumed to be 1.0. Unfortunately, no information regarding the value of the initial soil moisture fraction or the soil porosity is available. The MULTSED model estimates infiltration using a modified Green-Ampt approach[39] which combines porosity, average capillary suction, and initial and final soil moisture fractions into a single suction parameter, so errors in estimating porosity and initial soil moisture fraction may be compensated for in the average capillary suction value. Since these soils are silt loams, the average capillary suction range is -5 to -40 in.

The storm event of September 17, 1982 was simulated. For the summer of 1982, the land uses in HSL-1 and the remainder of HSL-3 are shown in Table 17. By September 17, each of these crops were fully mature, so HSL-1 has 42 percent ground cover and 58 percent canopy cover and the remainder of HSL-3 has 35 percent ground cover and 65 percent canopy cover for this storm event. For these types of cover, the ranges of potential interception are 0.01 to 0.05 in. for ground cover and 0.02 to 0.06 in. for canopy cover. Finally, using the "rule of thumb" established earlier, the ranges for ADW were estimated to be 2400-5800 and 3400-7500 for HSL-1 and the remainder of HSL-3, respectively.

The channels in HSL-3 are lined with earth and fine gravel, highly vegetated, and subjected to an appreciable amount of obstructions from rocks and branches. By comparing photographs of several channel cross sections of HSL-3 to the photographs in Figure 5.5 (typical channels showing different n values) of Chow's "Open Channel Hydraulics,"[40] a reasonable range of n is between 0.07 and 0.15.

Parameter Transfer for the Storm Event of September 17, 1982

On September 17, 1982, HSL-3 was subjected to 1.40 in. of rainfall over a 190 minute period. This storm produced the runoff hydrograph shown in Figure 14, a total runoff volume of 145.25 acre/ft (0.0456 in.), and a sediment yield of 140,000 lb (estimated from sediment concentration data).

To test the parameter and information transferability properties of MULTSED, the infiltration, interception, and roughness parameters were varied within the ranges determined from physical conditions until a good reproduction of the measured hydrograph was obtained. The predicted hydrograph for this event is compared to the measured hydrograph in Figure 14 (the predicted hydrograph has been shifted in time to permit a better comparison). The high quality of the match between the predicted and measured hydrographs is evidenced by the fact that the predicted total runoff volume is only 0.31 percent less than the measured volume, and the predicted peak discharge is only 8.9 percent less than the measured peak discharge.

The parameter values which lead to this excellent predicted hydrograph are displayed in Table 18. Once again, the usefulness of the hydrologic portion of MULTSED is demonstrated by the fact that all the parameters fit within their physically determined ranges and that the porosity data was transferred from LCT 1. Furthermore, it is encouraging that the "rule of thumb" for ADW provided an acceptable value for this storm on HSL-3. As previously mentioned, HSL-1 is also a gaged watershed so its roughness coefficients n and ADW were selected to try to produce a good fit of its measured hydrograph for this storm. Hence, they are a slightly out of their expected ranges.

[39] D. B. Simons, R. M. Li, and B. E. Spronk.

[40] V. T. Chow, *Open Channel Hydraulics* (McGraw-Hill, New York, 1959).

Table 17

Highland Silver Lake Watershed:
Land Use in the Summer of 1982

Land Use	HSL-1 (%)	Remainder of HSL-3 (%)
Soybeans	58	38
Wheat	41	28
Corn	-	23
Forrest	-	4
Miscellaneous Ground Cover	1	7

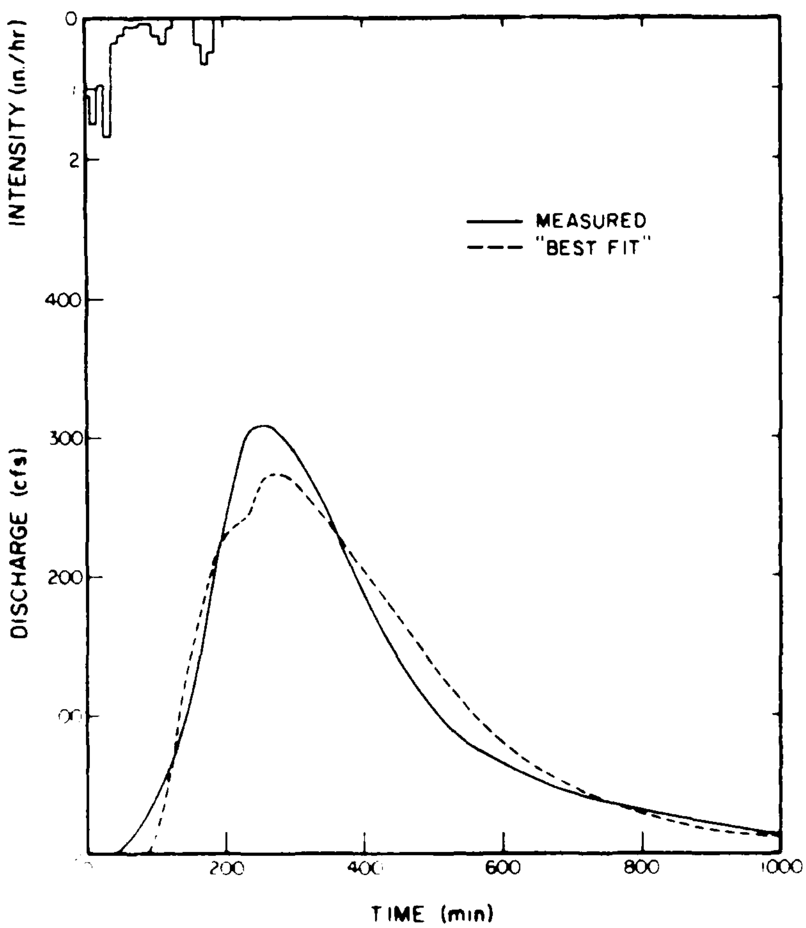

Figure 14. Comparison of measured and simulated hydrographs for the September 17, 1982 storm on HSL-3.

Table 18

Parameter Values for Good Reproduction of September 17, 1982 Storm Event on HSL-3

Parameter	HSL-1	Remainder of HSL-3
KH (in./hr)	0.056	0.056
h	0.45*	0.45*
SI	0.80	0.80
$-\psi$ (in.)	10.0	10.0
VC (in.)	0.03	0.03
VG (in.)	0.02	0.02
ADW	8000	7500
n	0.12	0.12 (SW2)
		0.15 (main chnl)

*Transferred from LCT 1.

For the predicted storm event of September 17, 1982 the maximum possible overland flow sediment transport capacity is 454,000 lbs. Thus, an intelligent selection of the raindrop splash detachment coefficient, a_1, will reproduce the measured sediment yield. HSL-3 is primarily an agricultural watershed, as are ISU-1 and ISU-2, the Illinois watersheds should be a good source of a_1 values for transfer to HSL-3. The August 15, 1977 storm on ISU-1 and ISU-2 produced unusually high detachment coefficients, while the April 19, 1977 storm on ISU-1 produced an unusually high sediment yield. If these storms are ignored, the range of raindrop splash detachment coefficients for ISU-1 and ISU-2 is 0.0007-0.0026 with a mean of 0.0013. Using this mean value of a_1 as an initial guess, the predicted sediment yield is 123,600 lbs which is 11.7 percent less than the measured sediment yield. If the median a_1 value (0.0017) is used as an initial guess, the predicted sediment yield is 147,700 lbs which is 5.5 percent greater than the measured sediment yield.

Based on the results obtained here, reasonable estimates of sediment yield may be obtained for ungaged watersheds if the transferred detachment coefficient values are carefully selected. However, there is a need for more calibration and verification of detachment coefficient transferability. Nevertheless, the results obtained here are enough to inspire optimism in the usefulness of MULTSED.

Calibration of Larger Watersheds

Since it will inevitably be necessary to study watersheds which are too large to accurately model as a single subwatershed unit, the multiple subwatershed and plane modeling capabilities of MULTSED must be used. Unfortunately, when a watershed is broken down into a number of units, formal optimization of the simulated hydrograph using the GRG-based program is no longer possible, and one must resort to iteration. Hence, a good fit is identified by iterating on the parameter values until a reasonable match is obtained between the measured and simulated hydrographs in terms of peak discharge, total runoff volume or both, which also allows the proper sediment yield to be reproduced. Such fits can be quite good, as was the case for the September 17, 1982

storm on HSL-3 (Figure 14), or for the March 18, 1983 storm on HSL-3 (Figure 15) as found by Lee and Camacho.[41]

The iteration process requires a "good feel" for both the watershed hydrology and the workings of the model to obtain a good fit within a reasonable number of iterations. However, when done carefully, excellent results as in Figures 14 and 15 may be obtained. From the course of this work two useful guidelines for iteration have been found:

1. If subwatersheds within the boundary of the larger watershed to be calibrated are also gaged (such as HSL-1 in HSL-3 or ISU-1 and ISU-2 in the Four Mile Creek watershed), these subwatersheds should be formally optimized as described here. Then the calibration information should be transferred, where appropriate, in modeling the entire watershed.

2. When formally calibrating the smaller watersheds in this report, each of the parameters tended consistently to be in a certain portion of its physically reasonable range. These same tendencies also held for HSL-3. Thus, by choosing KH from the lower portion; ADW, n, VG, and VC from the upper portion; and $-\psi$ from the middle of their respective physically reasonable ranges, a good starting point for iteration is obtained.

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[41] M. T. Lee and R. Camacho, "Application of Geographical Information System and Hydrologic Modeling to an Agricultural Watershed in Illinois," paper presented at Non-Point Pollution Abatement Symposium (Milwaukee, Wisconsin, April 23-25, 1985).

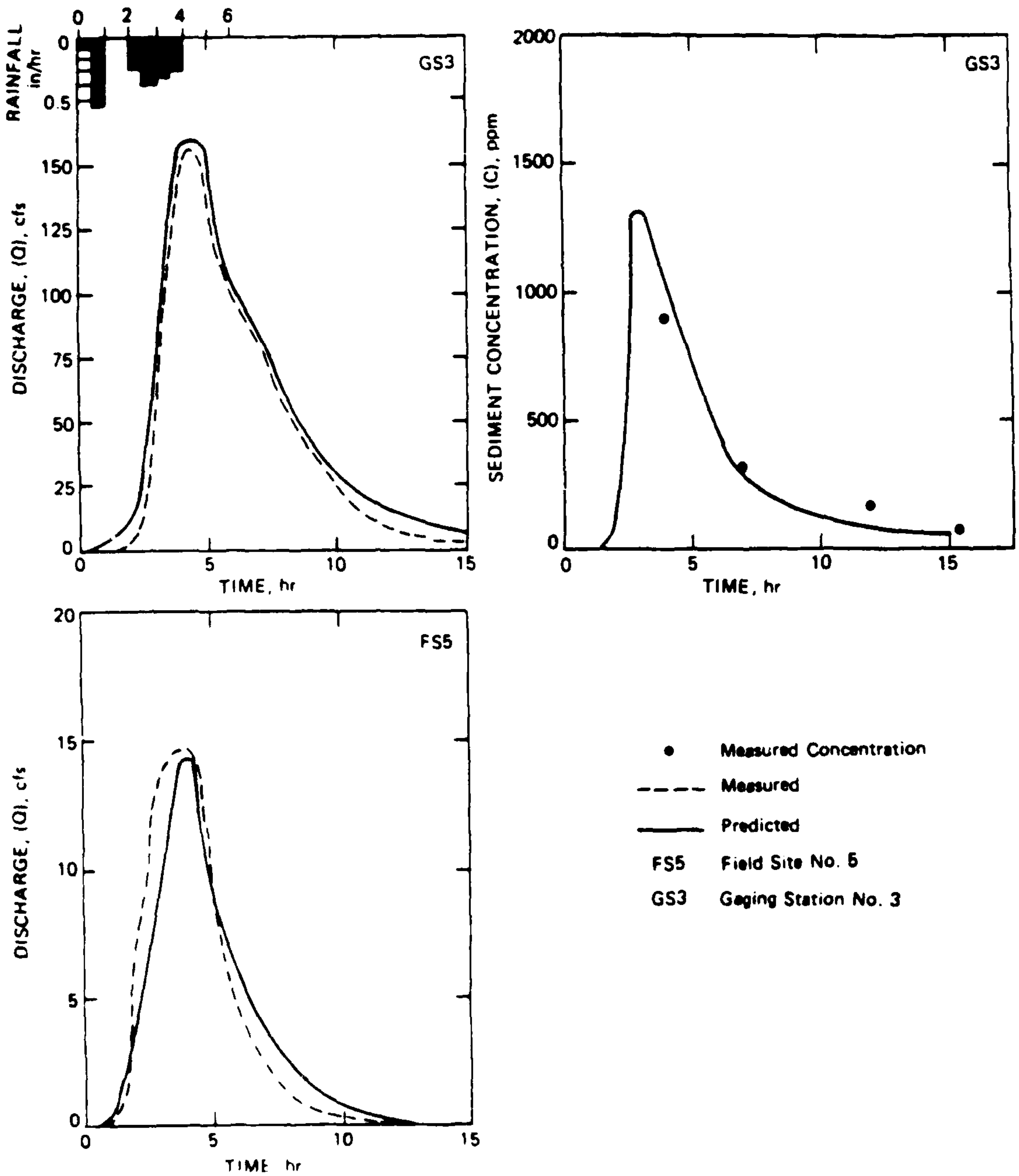

Figure 15. Runoff and sediment hydrographs for the March 18, 1983 storm on Highland Silver Lake Watershed, Highland, Illinois. (From M. T. Lee and R. Camacho, "Application of Geographical Information System and Hydrologic Modeling to an Agricultural Watershed in Illinois," paper presented at Non-Point Pollution Abatement Symposium (Milwaukee, Wisconsin, April 23-25, 1985).

7 CONCLUSIONS AND RECOMMENDATIONS

Conclusions

A description of the MULTSED model and a sensitivity study of the model parameters has been presented.

A procedure was presented to identify a reference rainfall or design storm which can be used to evaluate and plan erosion control measures.

The newly developed procedure for calibrating both the water and sediment yield is not strictly objective, but rather requires a good deal of judgment on the part of the user. Due to the nature of the MULTSED model, this procedure generally converges quickly (i.e., in about two iterations) to a solution with a good hydrograph fit and sediment transport capacities in excess of the measured sediment yield. The quality of the final "best fit" hydrograph obtained by this procedure is good and the calibrated parameter values for these "best fits" are consistent among similar watersheds. These high quality calibration results have allowed some important conclusions about the usefulness of MULTSED to be drawn.

The flexibility and parameter transferability characteristics of the hydrologic portion of MULTSED have been shown by the very favorable results of the calibration of 17 storm events on 5 small watersheds in the midwestern U.S. More importantly, the transferability of information on parameters important to MULTSED's sediment yield prediction has been shown for a large watershed. Therefore, for any watershed, ranges for the parameters used in MULTSED may be determined from that watershed's physical conditions or by transferring information from similar watersheds. Thus, MULTSED can provide reasonable predictions of water and sediment yield from any storm by using sensitivity analysis over the parameter value ranges for the watershed being studied. This is very important for the evaluation of watershed management strategies.

Finally, much more information on the proper values of the maximum overland flow resistance coefficient, ADW, and the rain drop splash detachment coefficient, a_1, is needed to develope rules on how to determine their values based on physical conditions (e.g., relating a_1 to land use and soil type, or relating ADW to ground cover percent and total overland flow resistance, K_g). Additional calibration experience with the model should assist in providing this information.

Recommendations

Experience with the model has uncovered some recommended corrections and improvements. These are listed below.

Corrections

1. Wetted perimeter calculation in MSED1.

2. Channel infiltration calculation in MSED3.

3. Inconsistency in computing resistance factor in MSED1 and MSED3.

4. Inconsistency in the use of the Einstein equation for suspended load in MSED1 and MSED3.

5. Calculation of the amount of bare soil in MSED1 for determining the effect of ground cover on raindrop splash detachment.

Improvements

1. The number of reaches (NDX) used in the channel routing in the current MSED3 is internally fixed at five. Based on tests in which this varied, it is recommended that NDX be user-specified and a value of at least 10 be used.

2. Currently, the geometric mean of the two largest sediment sizes is used to determine the effective particle shear stress and the bed layer thickness in Einstein's equation. This practice allows these sizes to strongly influence sediment transport capacity. However, the specifications of the sediment size distribution is provided by the user and the amount of erodible sediment represented by the two largest sizes may be very small. Furthermore, the user is not made aware of the significance of the choice of sediment sizes specified. The model should therefore be modified to remove this dependency of transport capacity on the two largest sediment sizes specified by the user. Study indicates that a bed layer thickness of 4.8 in. be used for particles less than 2.4 in. in diameter, and a thickness of twice the particle diameter for particles larger than 2.4 in.

3. MULTSED currently estimates the exponent of the suspended sediment distribution, z_r, using the shear velocity corresponding to the total boundary resistance. However, the development of the suspended bed load relationship used in the model indicates that it is proper to use the shear velocity corresponding to the flow resistance caused by the individual grains.

4. The original Meyer-Peter, Muller bed load relation was derived primarily from laboratory flume experiments with channel slopes between 0.04 and 2.0 percent. In 1984, Smart published the results of further experiments for channels with slopes ranging from 3 percent to 20 percent. Smart found that the Meyer-Peter, Muller equation seriously underestimates sediment transport capacity on slopes steeper than 3 percent. Furthermore, the Meyer-Peter, Muller formulation using Shields' critical shear stress provides greatly improved performance for these steeper slopes. Smart developed a simple equation based on Meyer-Peter and Muller's original reasoning and Shields' critical shear stress with an adjustment to it for bed slope. The resulting equation fit both his and Meyer-Peter and Muller's data extremely well.

Based on Smart's results, it may be that the low transport capacities obtained after the initial hydrologic calibration may be due to inadequacies in the Meyer-Peter, Muller relation for the steep overland slopes encountered, as opposed to inadequacies in the kinematic wave routing. By incorporating Smart's equation into MULTSED, both the hydrologic and sediment calibration may be improved and simplified. This requires future study.

METRIC CONVERSIONS

1 in. = 25.4 mm

1 ft = 0.305 m

1 lb = 0.453 kg

1 mi = 1.6 km

1 cu ft = 0.028 m^3

1 sq mi = 2.6 km^2

1 acre = 0.405 ha

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APPENDIX A: EXAMPLE DATA FILES FOR MULTSED

ISU-2 is modeled as a single "open book" subwatershed unit by MULTSED. In order to perform the simulation of ISU-2, MULTSED requires two data files. Tape 1 contains all the physical parameters of the subwatershed unit, and Tape 2 contains the computational sequence, total time of hydrograph, and the simulation title.

The portion of the Walnut Gulch watershed used for modeling is the system composed of subwatershed unit 33, plane units 25 and 26, and channel unit 9 (see Figure 2 in Chapter 3). Modeling this system requires the use of the multiple watershed capabilities of MULTSED, and thus four data files are required. Tape 1 and Tape 2 contain the same type of information as for ISU-2. Tape 9 contains the computational sequence for the channel, time increment, total time of hydrograph, and simulation title. Tape 10 contains all the physical parameters for the channel unit.

Typical Tape 1 Data File for Modeling ISU-2 with MULTSED

```
1
2UNIFORM HYETOGRAPH - DURATION = 5 MIN, 10-YEAR STORM
3 SUBWATER 1 2
4 0.160      0.475     0.77     1.0     3.5
5 0.160      0.475     0.77     1.0     3.5
6 0.0        0.0       99       0.01    0.0
7 0.0        0.0       99       0.01    0.0
8 0.05625    240
9 0.06744    280
10 0.03254   1300
11 1         70        0.060            0.0      0.0     5000
12 7.200     5.00
13 0.05      2.0       0.85     1.00    0.047    5
14 0.002     0.05
15 0.01      0.13
16 0.02      0.63
17 0.2       0.69
18 0.5       1.0
```

Typical Tape 2 Data File for Modeling ISU-2 with MULTSED

```
1UNIFORM HYETOGRAPH - 10-YEAR STORM, DURATION = 5 MIN
2 2.00       100
3 0          1
4 1          2         1
```

Typical Tape 1 Data File for Modeling Walnut Gulch with MULTSED

```
1
2WALNUT GULCH; UNIFORM HYETOGRAPH, DEPTH = 4 IN, DURATION = 70 MIN
3 SUBWATER33  2
4 0.60       0.40      0.60     1.00    1.00
```

Typical Tape 1 Data File for Modeling Walnut Gulch with MULTSED (Cont'd)

0.60	0.40	0.60	1.00	1.00		
38.0	0.05	33.0	0.01	0.0		
38.0	0.05	33.0	0.01	0.0		
0.061	2097					
0.053	2310					
0.0153	28000					
1	70.0	0.030		0.0	0.0	3000
3.4286	70.0					
0.01	2.0	1.0	1.0	0.047	9	
0.002	0.15					
0.05	0.55					
0.5	0.72					
1.0	0.82					
1.5	0.89					
2.0	0.94					
3.0	0.97					
4.0	0.99					
25.0	1.00					
PLANE 25	1					
0.60	0.40	0.70	1.0	1.0		
25.0	0.05	33.0	0.01	0.0		
0.05	916					
0.0153	29000					
1	70	0.030		10.0	0.365	3000
3.4286	70.0					
0.01	2.0	1.0		0.047	9	
0.002	0.15					
0.05	0.55					
0.5	0.72					
1.0	0.82					
1.5	0.89					
2.0	0.94					
3.0	0.97					
4.0	0.99					
25.0	1.00					
PLANE 26	1					
0.60	0.40	0.70	1.0	1.0		
25.0	0.05	33.0	0.01	0.0		
0.046	1492					
0.0153	29000					
1	70.0	0.030		10.0	0.365	3000
3.4286	70.0					
0.01	2.0	1.0		0.047	9	
0.002	0.15					
0.05	0.55					
0.5	0.72					

Typical Tape 1 Data File for Modeling Walnut Gulch with MULTSED (Cont'd)

```
61 1.0           0.82
62 1.5           0.89
63 2.0           0.94
64 3.0           0.97
65 4.0           0.99
66 25.0          1.00
```

Typical Tape 2 Data File for Modeling Walnut Gulch with MULTSED

```
 1 WALNUT GULCH; UNIFORM HYETOGRAPH, DEPTH = 4", DURATION = 70 MIN
 2 5.00          450
 3 2             1
 4 1             2            1
 5 2             1            1
 6 3             1            1
```

Typical Tape 9 Data File for Modeling Walnut Gulch with MULTSED

```
 1 WALNUT GULCH; UNIFORM HYETOGRAPH, DEPTH = 4", DURATION = 70 MIN
 2 5.0           450
 3 2             1            0            0            1          9
 4 1      1                   1      2     0
```

Typical Tape 10 Data File for Modeling Walnut Gulch with MULTSED

```
 1
 2 CHANNEL NUMBER 9
 3 1
 4 29000         0.0153       1.0          0.40         0.80       1.0        2.0
 5 0.030                      70.0
 6 10.0          0.365        12.10        0.362        0.056      1.5        1.0      0.047
 7 0.002         0.10
 8 0.05          0.16
 9 0.5           0.22
10 1.0           0.28
11 1.5           0.33
12 2.0           0.46
13 3.0           0.62
14 4.0           0.80
15 25.0          1.00
```

APPENDIX B: ESTIMATION OF WATERSHED TIME OF CONCENTRATION

A method developed by Kirpich[42] in 1940 is the only commonly used method which directly estimates the time of concentration. The Kirpich method is an empirical formula, developed for use of small agricultural watersheds ranging from 1 to 500 acres in size. The Kirpich method is given by the following equation:

$$t_c = c_c L^{0.77} / s^{0.385} \qquad \text{[Eq B1]}$$

where L = the flow path length along the channel from the outlet to the basin upstream boundary; s = the slope computed as the difference between the elevation at the ends of L divided by L; and c_c = a constant which is 0.078 for L in ft.

Most of the other methods for estimating time of concentration do so by summing overland flow time and channel flow time. Three common methods exist for estimating overland flow time. Of these, only Kerby's method[43] does not require prior specification of rainfall intensity. Therefore, in this study, Kirpich's method and Kerby's method will be used a guides in the estimation of the time of concentration.

Kerby's method is valid for watersheds with overland flow lengths less than 1200 ft. Kerby's method is given by the following equation:

$$t_o = C_K \, (N L_o s^{-0.5})^{0.467} \qquad \text{[Eq B2]}$$

where L_o = the overland flow length; s = the overland slope; N = a correction factor which accounts for the surface conditions; and C_K = a constant which is 1.44 for L_o in in. and 0.83 for L_o in ft.

ISU-2 Time of Concentration, t_c

ISU-2's dimensions for use in Kirpich's method are L = 1480 ft and s = 0.02162. Thus, t_c was estimated to be 9.5 minutes.

For use in Kerby's method, ISU-2's dimensions must be defined by left and right planes. For the left plane, L_o is 240 ft and s is 0.05625 and for the right plane L_o is 280 ft and s is 0.06744. The watershed was judged to be a "moderately rough bare surface" and so N was taken as 0.2. With these inputs, t_o for the left and right planes was estimated to be 9.8 and 10.2 minutes, respectively.

Based on the estimates provided by these two equations, a t_c of 15 minutes seems reasonable. This allows a 5 minute channel flow time, which is short for a 1300 ft channel, but considering one method estimates t_c to be 9.5 minutes; this 15-minute

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[42] *Introduction to Hydrosystems Engineering Class Notes* (Department of Civil Engineering, University of Illinois, 1983), p 128.

[43] *Introduction to Hydrosystems Engineering Class Notes*, pp 126-127.

estimate seems reasonable. Furthermore, an estimated t_c of 15 minutes is very convenient to work with from a practical standpoint.

Walnut Gulch Subwatershed 33 Time of Concentration, t_c

Subwatershed 33 has an area of 2833 acres and overland flow lengths of 2097 ft and 2310 ft for the left and right planes, respectively. Clearly, these dimensions violate the validity bounds on both Kirpich's and Kerby's methods. Nevertheless, these methods shall be used to provide guidelines for estimating t_c for this watershed because of the lack of any other simple methods.

Subwatershed 33 dimensions for use in Kirpich's method are L = 28000 ft and s = 0.0153. Thus, t_c was estimated to be 104 minutes.

For use in Kerby's method, the left plane dimensions are L_o = 2097 ft and s = 0.061, and the right plane dimensions are L_o 2310 ft and s = 0.053. The watershed was judged to be "poor grass" and so N was taken to be 0.2. With these inputs, to for the left and right planes was estimated to be 26.7 and 28.9 minutes, respectively.

A 90 minute channel flow time seems reasonable, thus making t_c 120 minutes, which agrees fairly well with Kirpich's method. Furthermore, an estimated t_c of 120 minutes is very convenient to work with from a practical standpoint.

General Approach

In addition to the above equations, the model itself can be used to estimate t_c. This should be done on the basis of individual watershed units rather than the watershed as a whole if it contains channel units. The procedure is to use a uniform intensity rainfall of sufficient duration to allow the outflow to achieve a near steady state condition. Run the model and examine the outflow hydrograph from each unit and note the required time for approximately 95 percent or more of the steady state outflow to occur. Use this time as the estimate of t_c for that unit. The intensity should be high enough to exceed infiltration losses. An intensity with a return period of 5 years should be adequate. Each watershed unit (subwatershed or plane) should be evaluated separately.

Applying this procedure to the Walnut Gulch (subwatershed 33) and ISU-2 watersheds discussed in Chapter 3, the following estimates resulted:

Walnut Gulch	- 70 minutes
ISU-2 (1 percent ground cover)	- 15 minutes
ISU-2 (99 percent ground cover)	- 23 minutes

The values of t_c used in plotting Figures 6 through 9 were 120 minutes for Walnut Gulch and 15 minutes for ISU-2. If the above estimates were used instead, a horizontal shifting of the curves in these figures would result.

APPENDIX C: COMPARISON OF MEASURED AND SIMULATED HYDROGRAPHS*

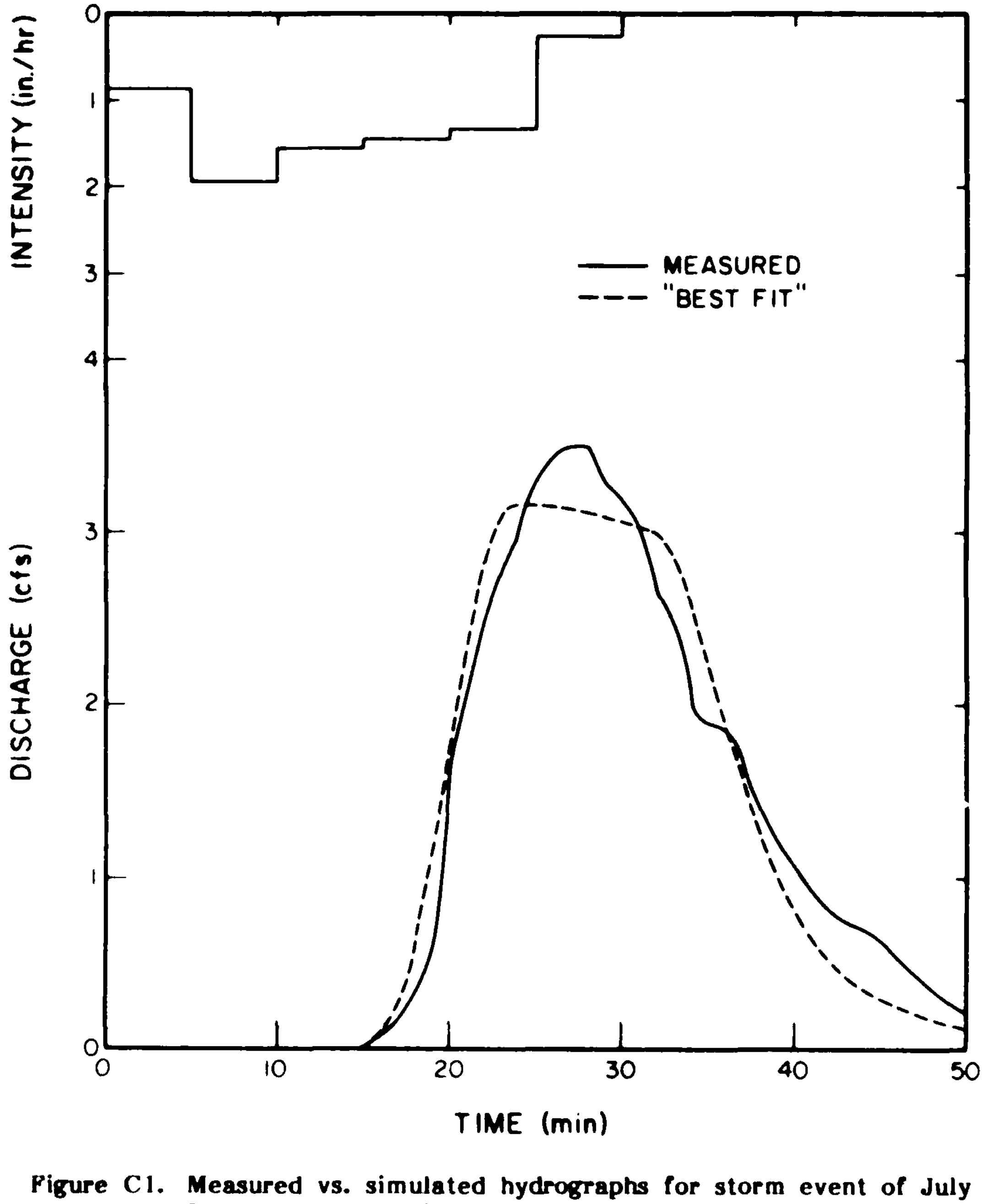

Figure C1. Measured vs. simulated hydrographs for storm event of July 21, 1982 on LCT 1 (Note: measured sediment yield = 2190 lb).

*Lawson Creek data are preliminary and were supplied by the U.S. Geological Survey, Urbana, Illinois.

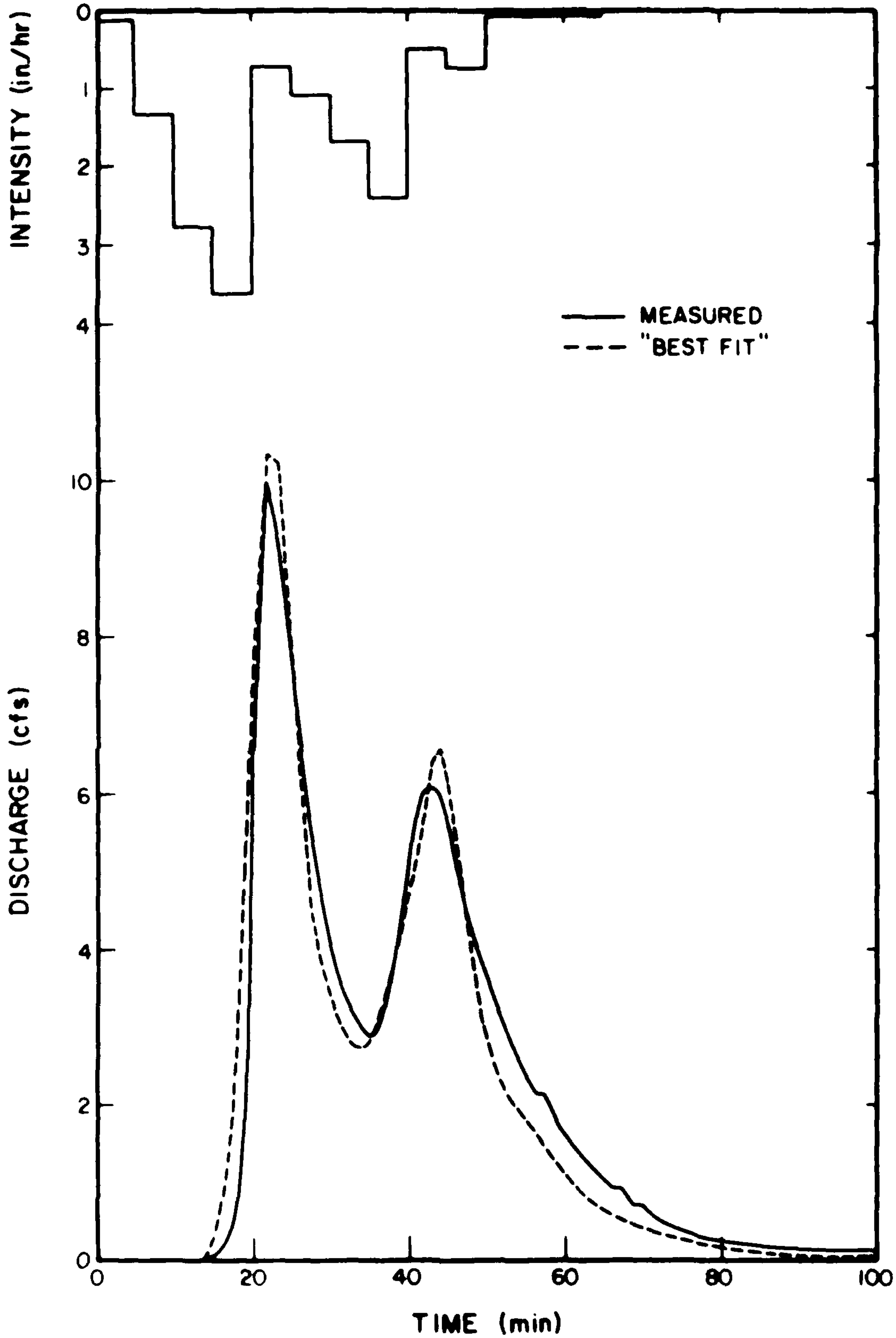

Figure C2. Measured vs. simulated hydrographs for storm event of November 1, 1982 on LCT 1 (note: measured sediment yield = 2180 lb).

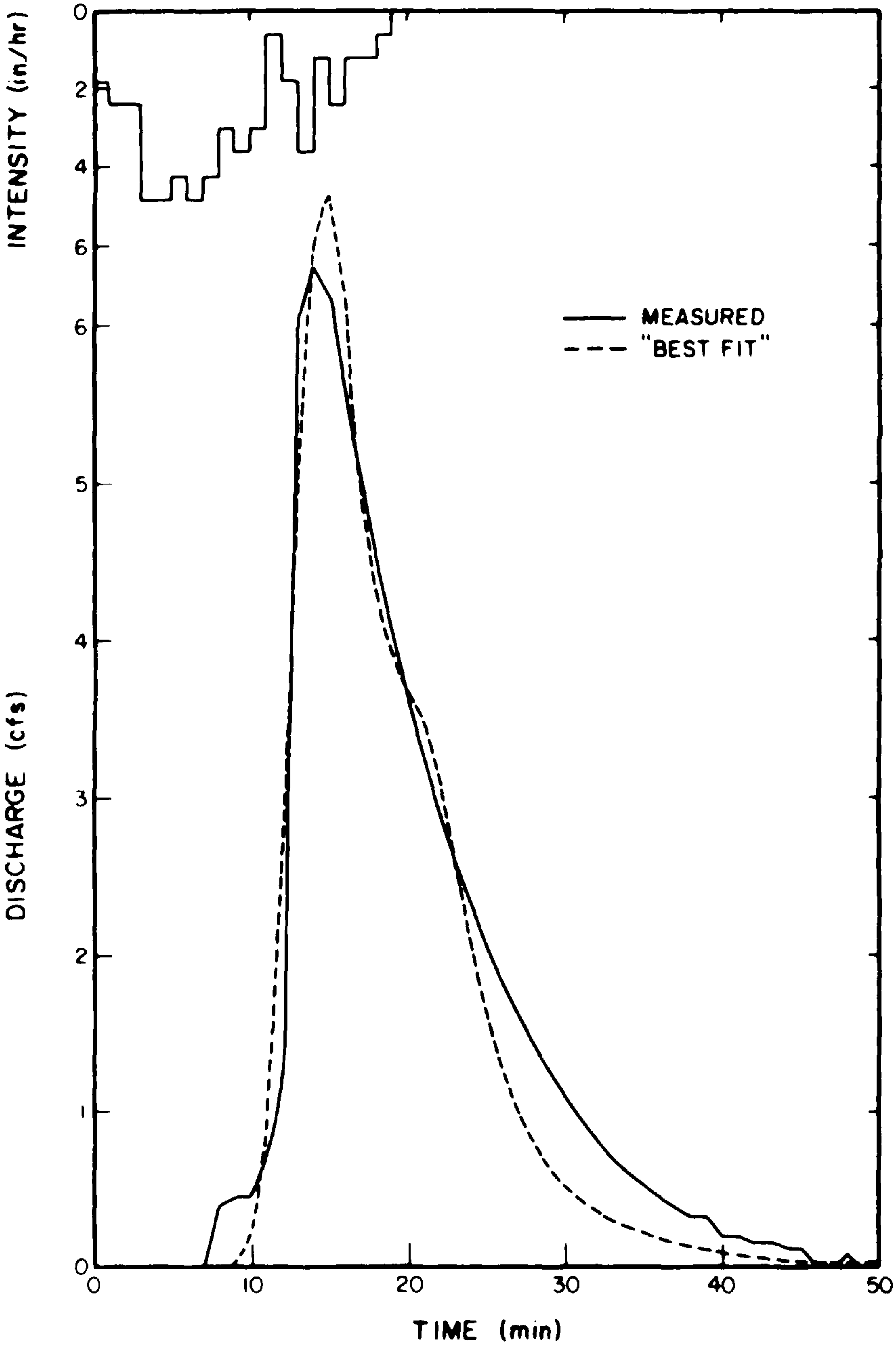

Figure C3. Measured vs. simulated hydrographs for storm event of June 29, 1983 on LCT 1 (note: measured sediment yield = 3830 lb).

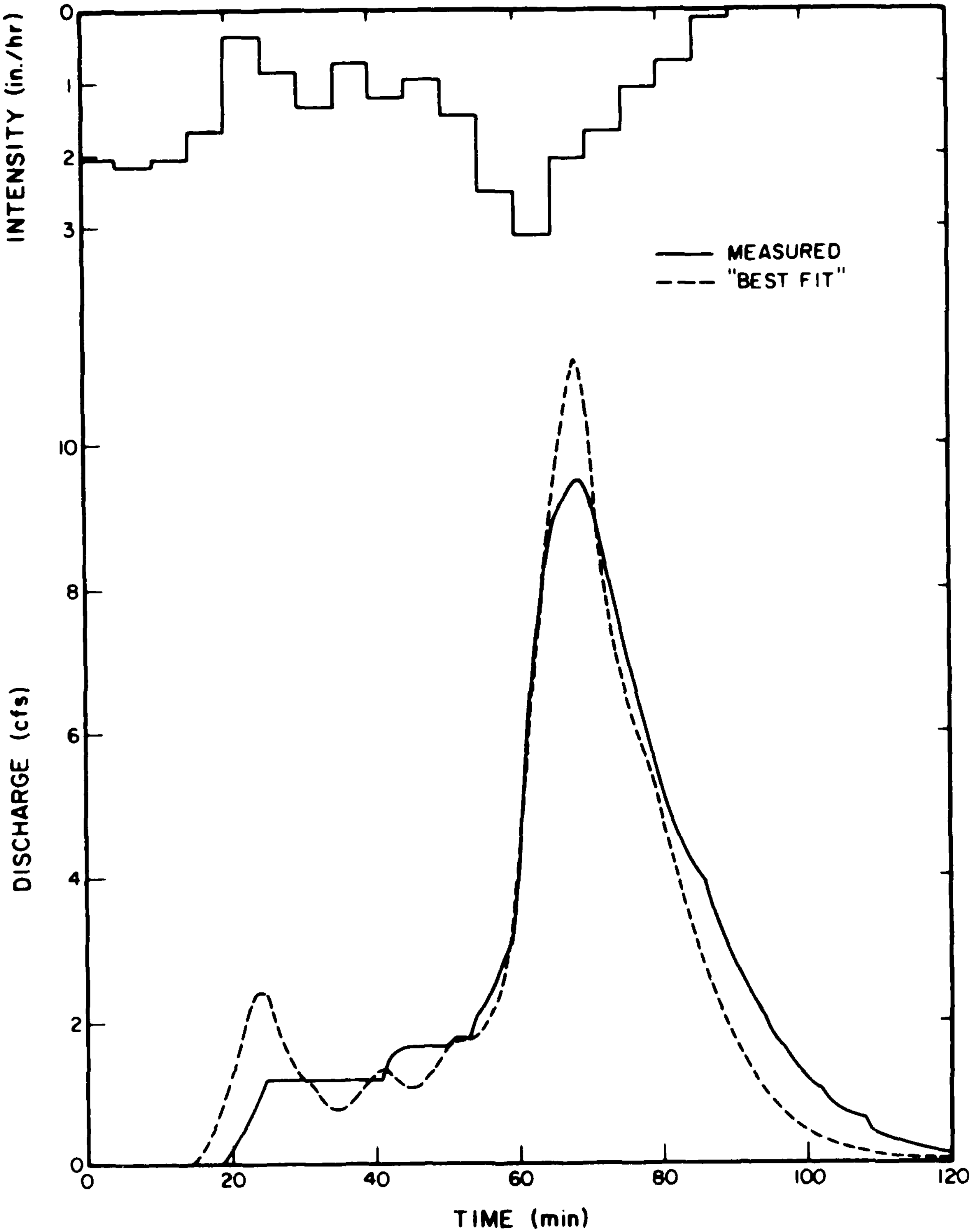

Figure C4. Measured vs. simulated hydrographs for first storm event of July 30, 1983 on LCT1P (note: measured sediment yield = 13,960 lb).

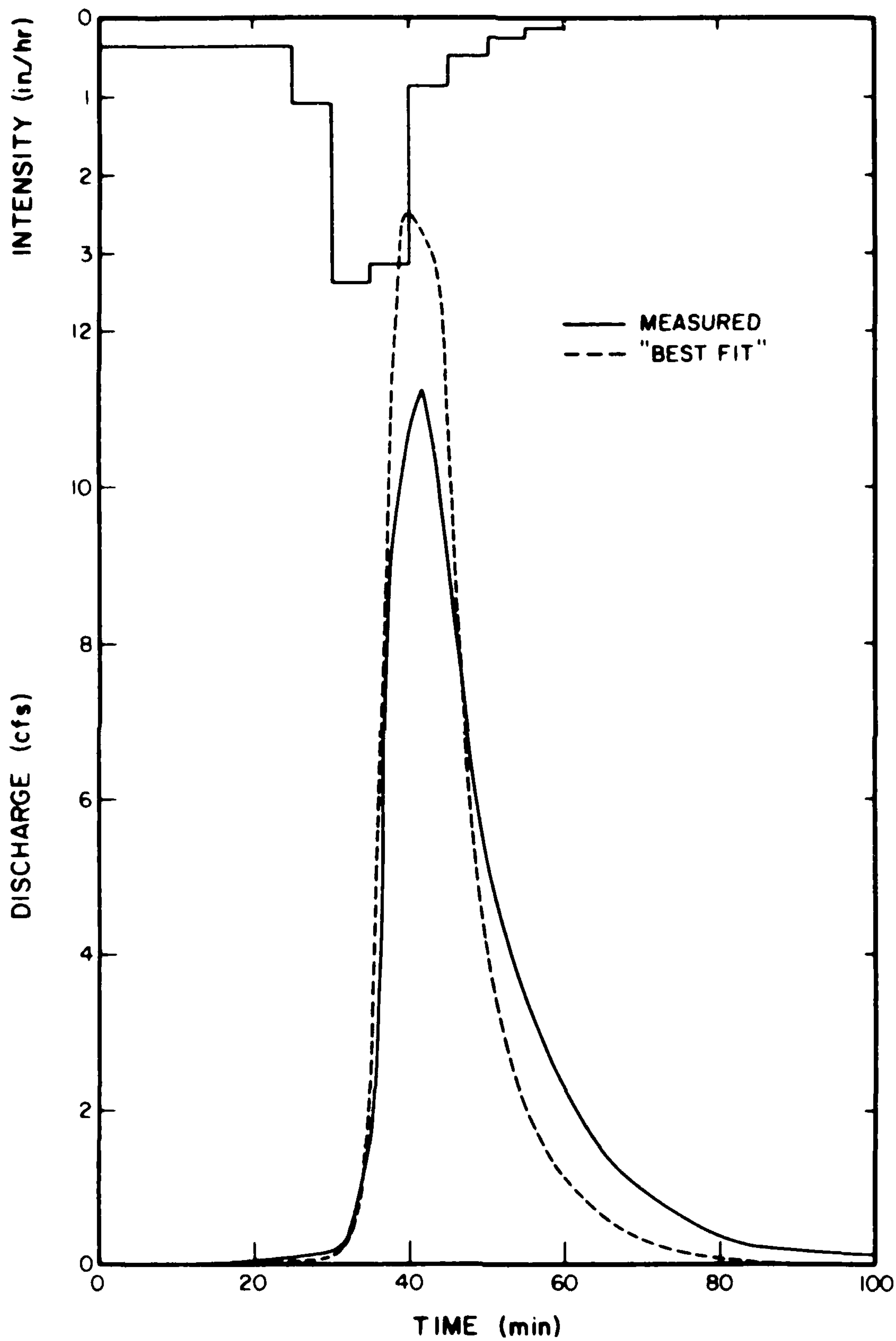

Figure C5. Measured vs. simulated hydrographs for second storm event of July 30, 1983 on LCT1P (note: measured sediment yield = 9970 lb).

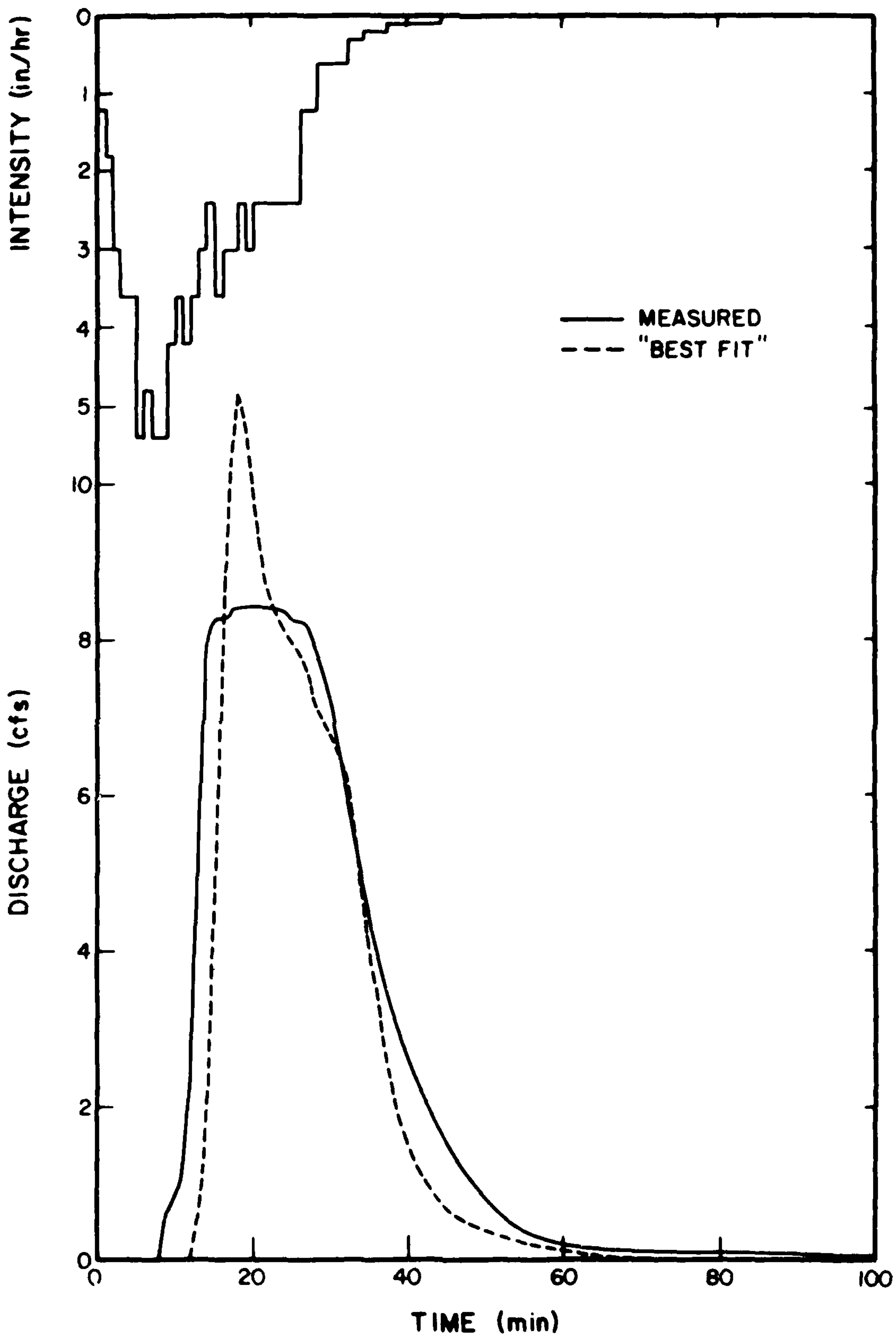

Figure C6. **Measured vs. simulated hydrographs for storm event of August 26, 1983 on LCT1P (note: measured sediment yield = 11,520 lb).**

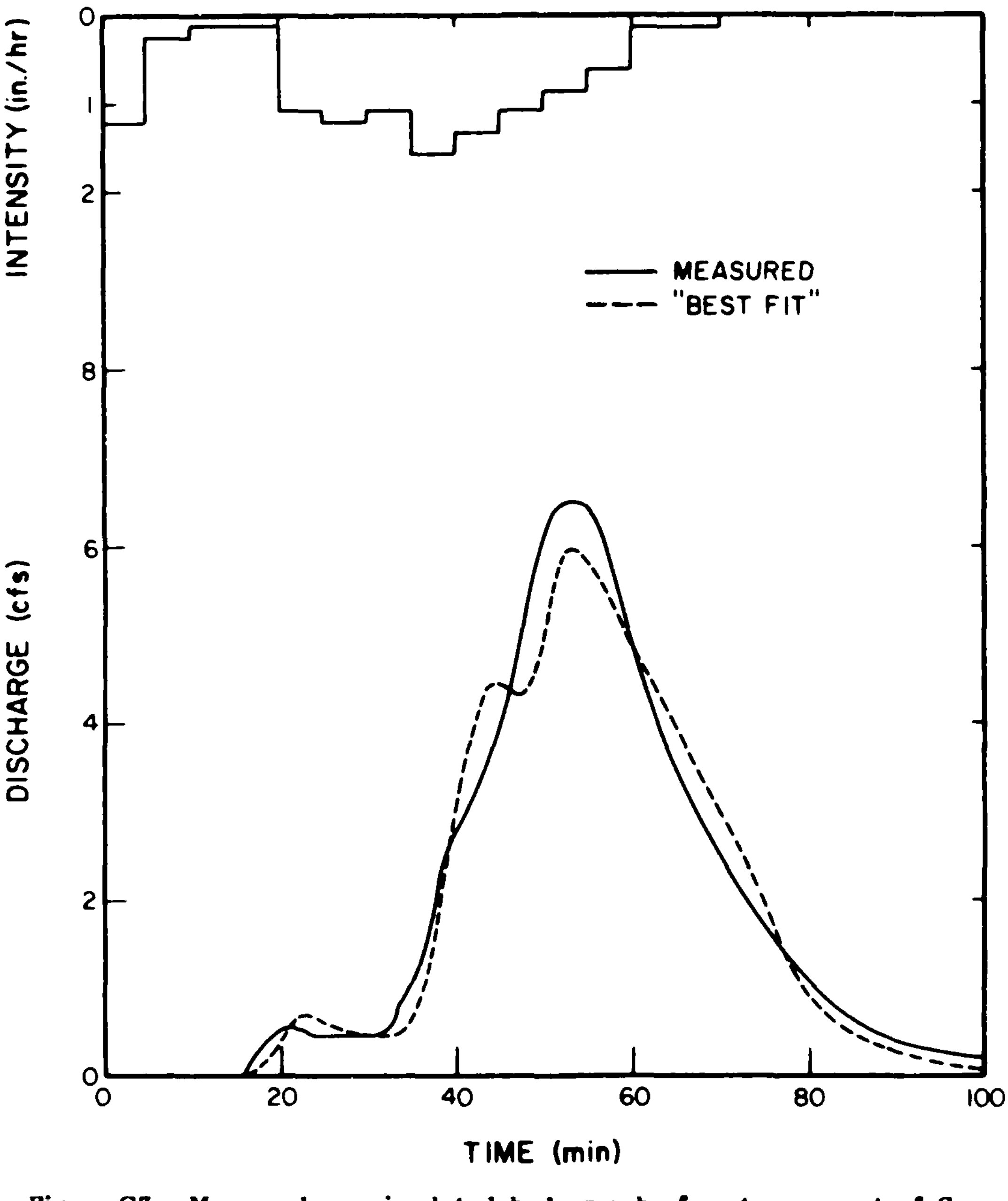

Figure C7. Measured vs. simulated hydrographs for storm event of September 18, 1983 on LCT1P (note: measured sediment yield = 8510 lb).

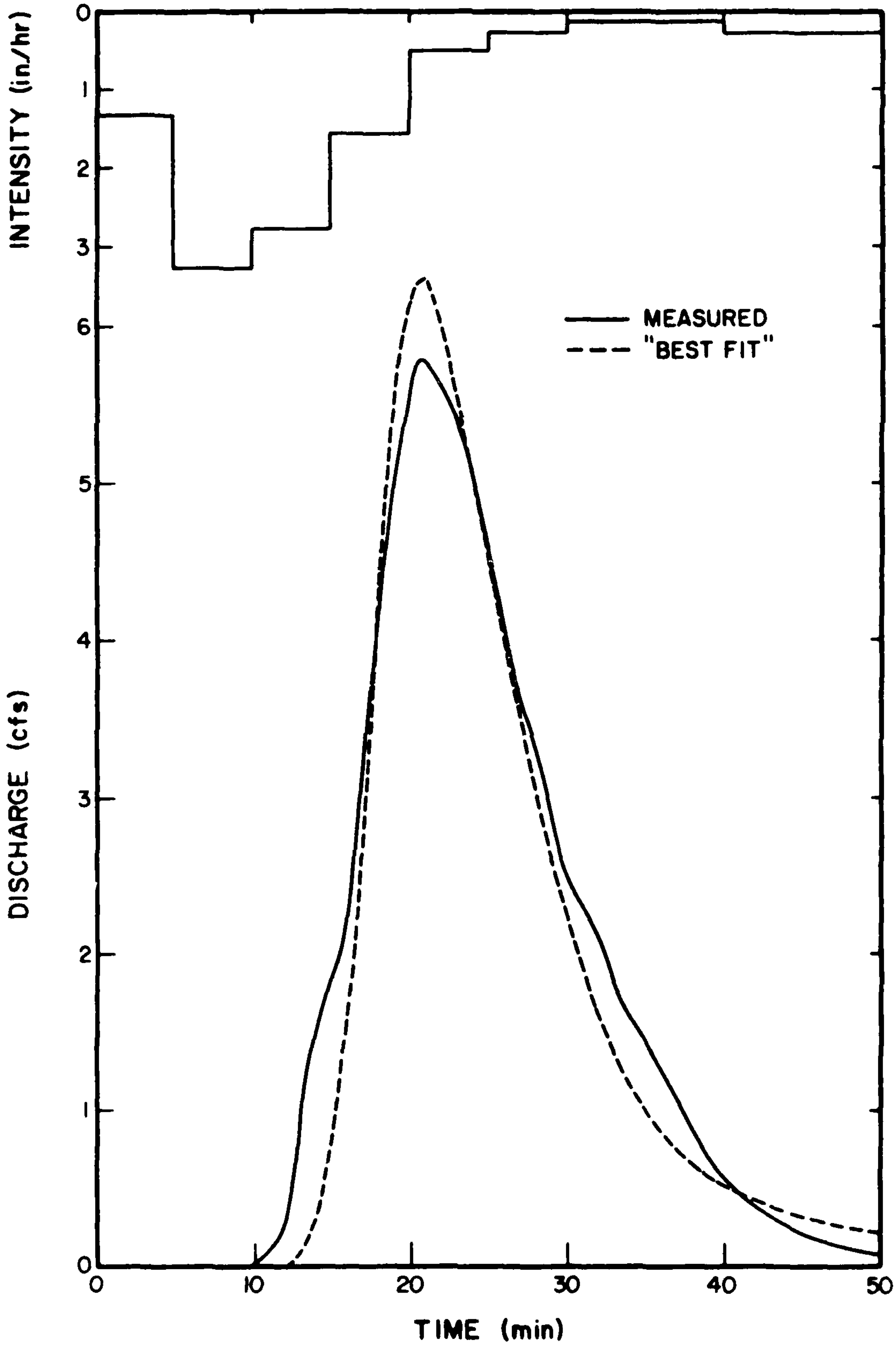

Figure C8. Measured vs. simulated hydrographs for storm event of May 25, 1984 on LCT1P2 (note: measured sediment yield = 500 lb).

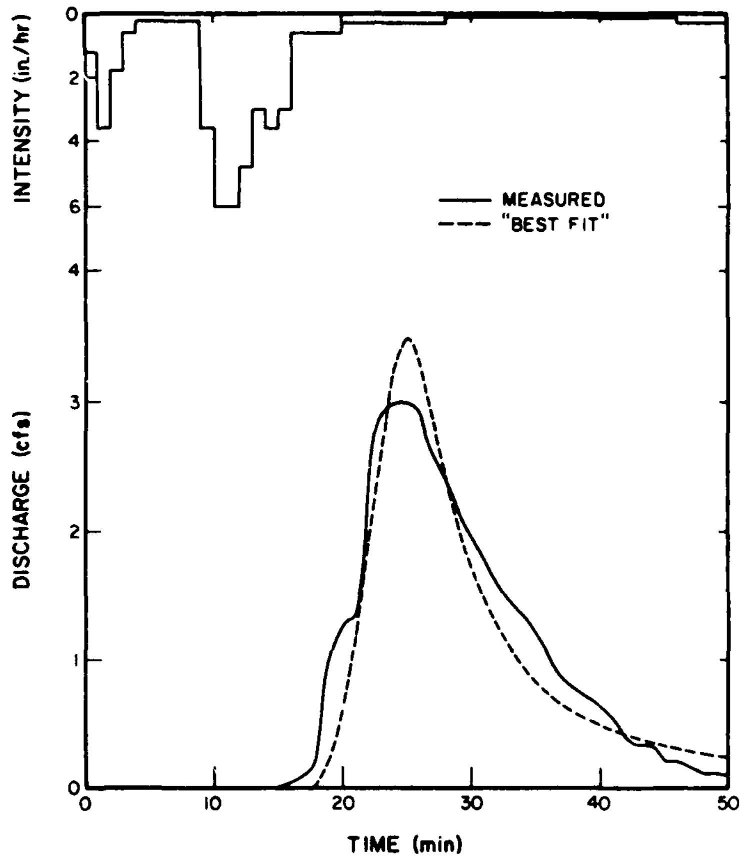

Figure C9. Measured vs. simulated hydrographs for storm event of June 6, 1984 on LCT1P2 (note: measured sediment yield = 180 lb).

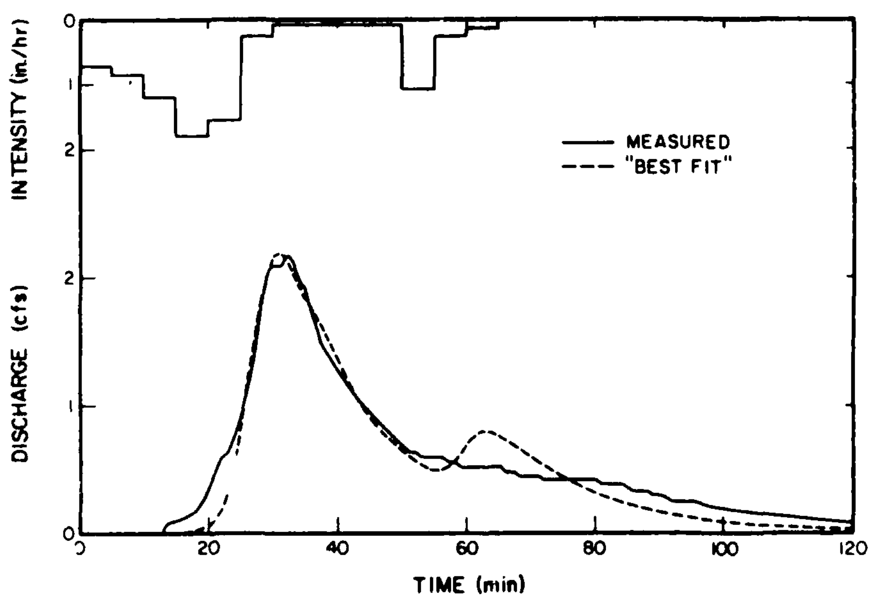

Figure C10. Measured vs. simulated hydrographs for storm event of October 31, 1984 on LCT1P2 (note: measured sediment yield = 35 lb).

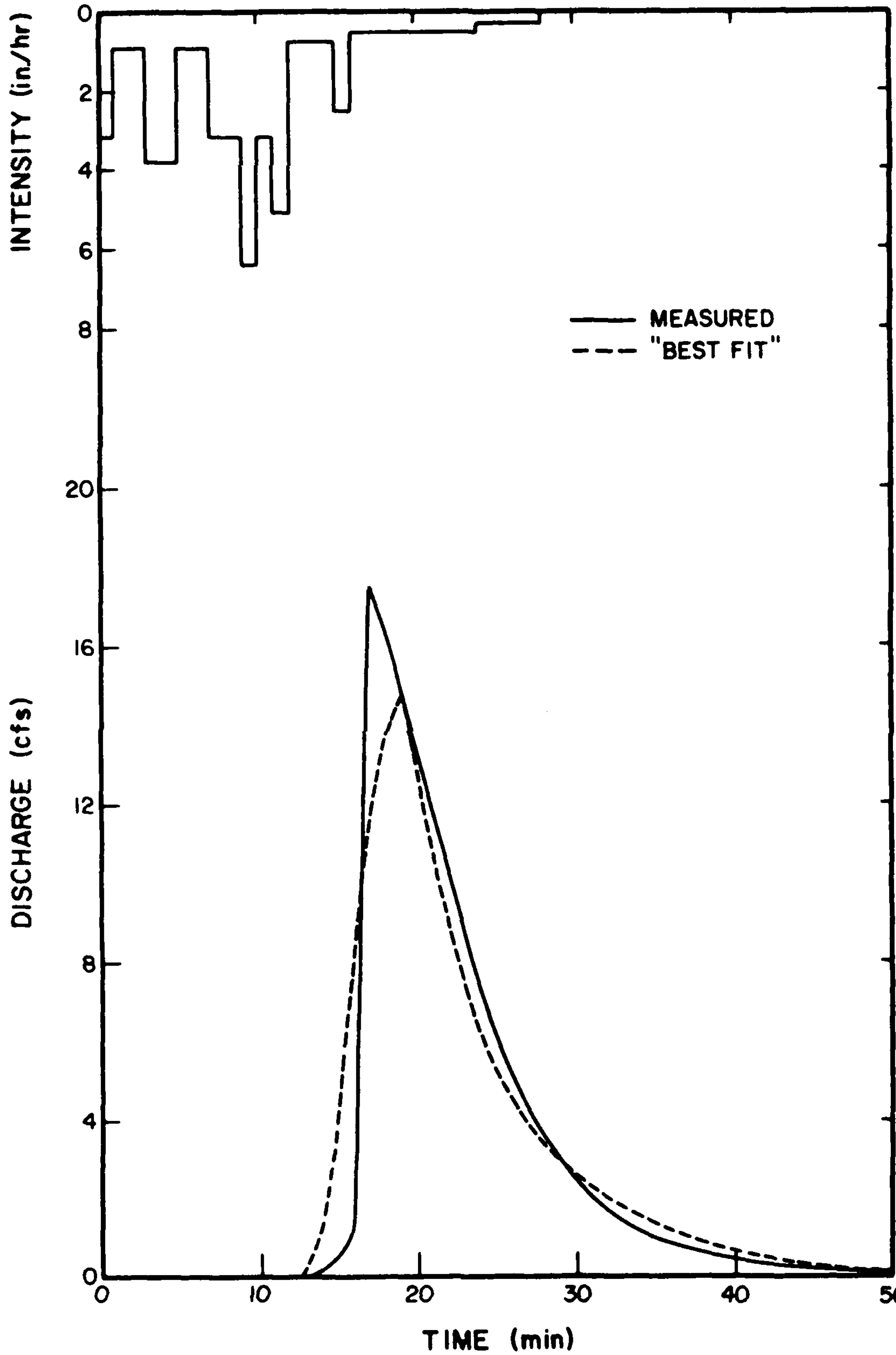

Figure C11. Measured vs. simulated hydrographs for storm event of April 19, 1977 on ISU-1 (note: measured sediment yield = 33,120 lb).

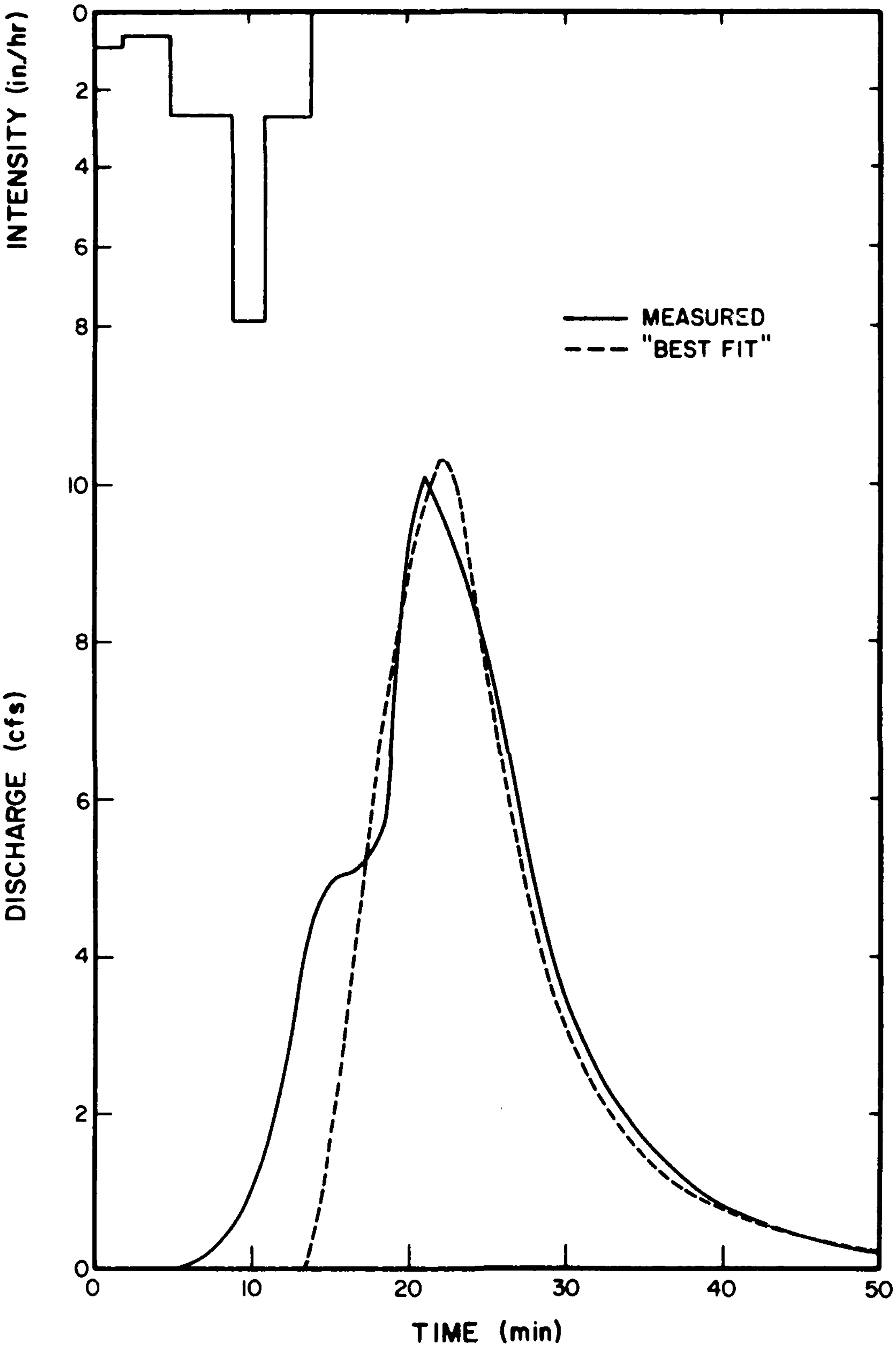

Figure C12. Measured vs. simulated hydrographs for storm event of August 15, 1977 on ISU-1 (note: measured sediment yield = 8550 lb).

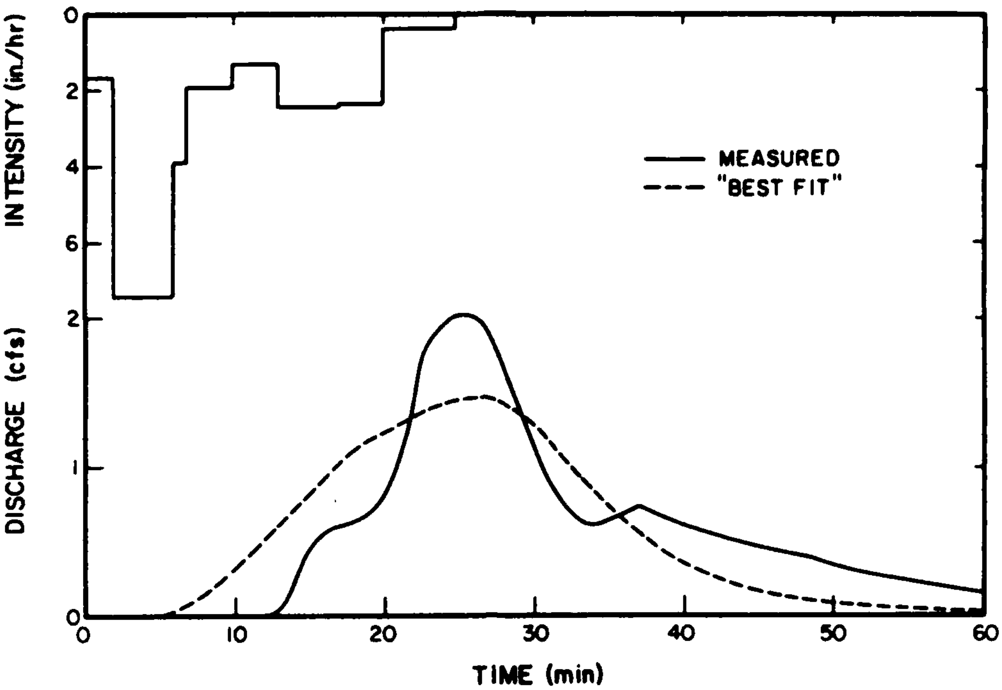

Figure C13. Measured vs. simulated hydrographs for storm event of May 27, 1978 on ISU-1 (note: measured sediment yield = 3490 lb).

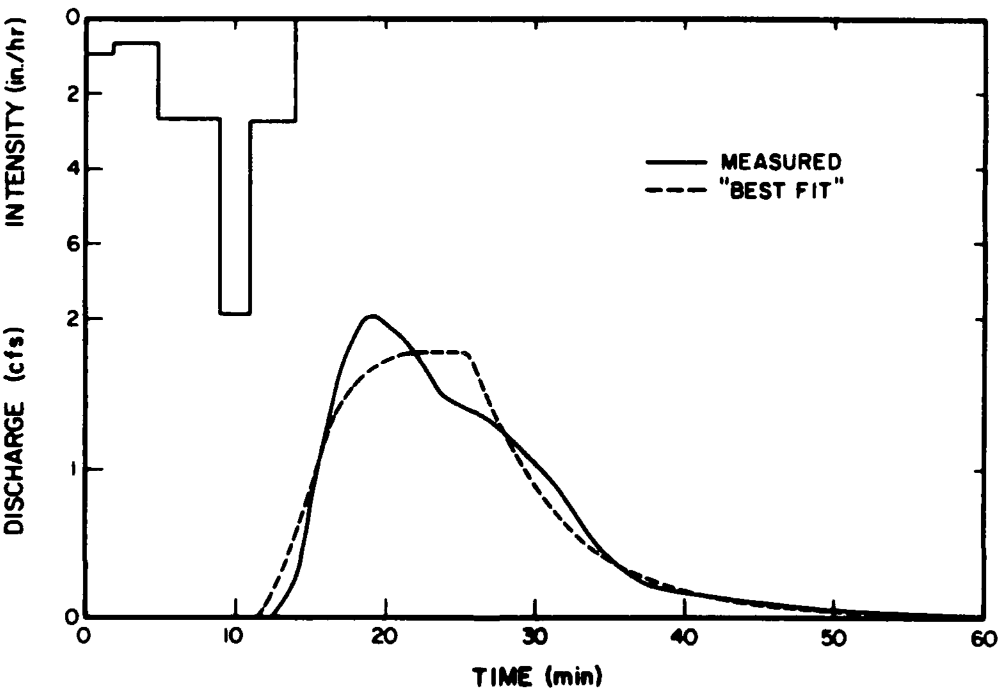

Figure C14. Measured vs. simulated hydrographs for storm event of August 15, 1977 on ISU-2 (note: measured sediment yield = 2280 lb).

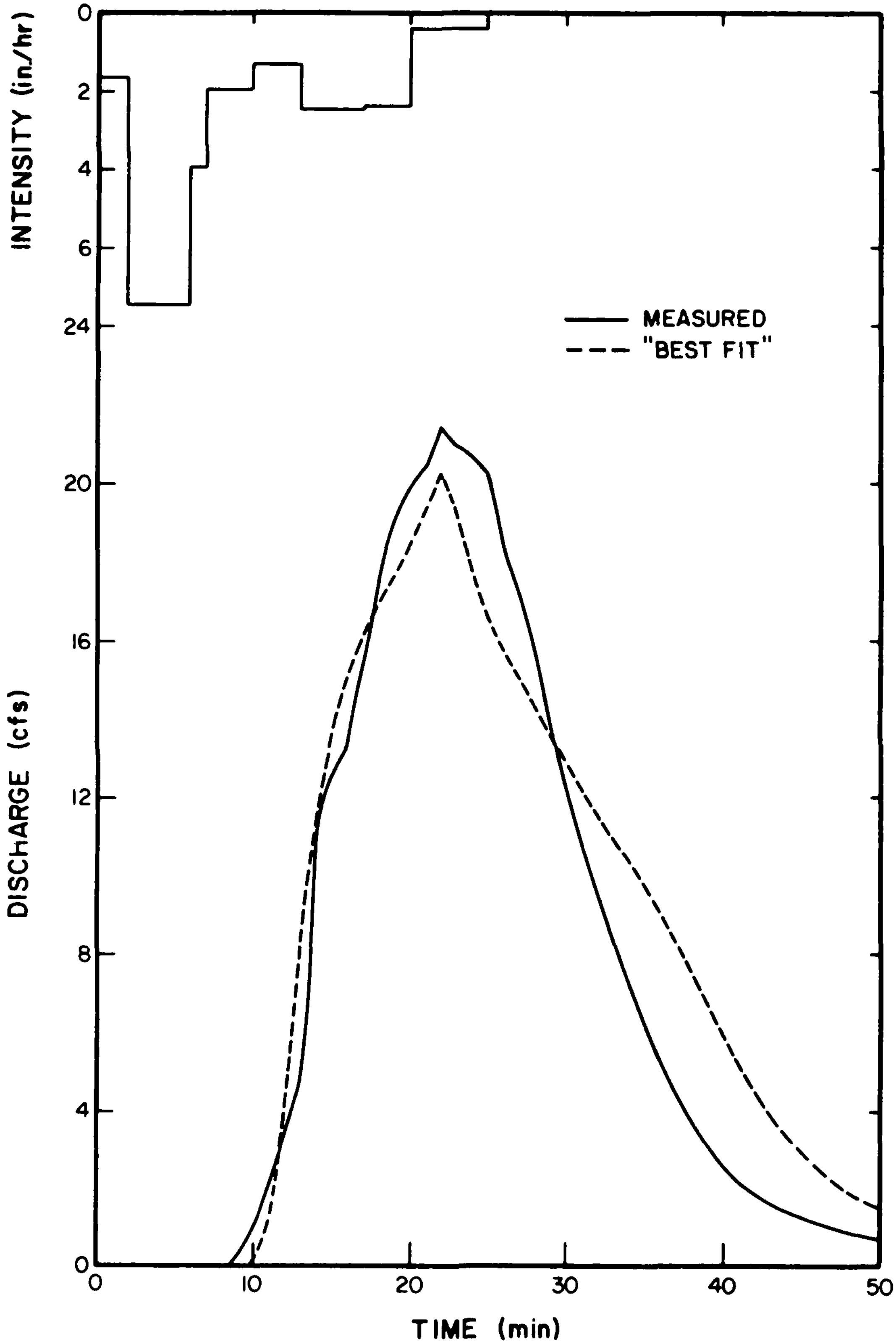

Figure C15. Measured vs. simulated hydrographs for storm event of May 27, 1978 on ISU-2 (note: measured sediment yield = 25,000 lb).

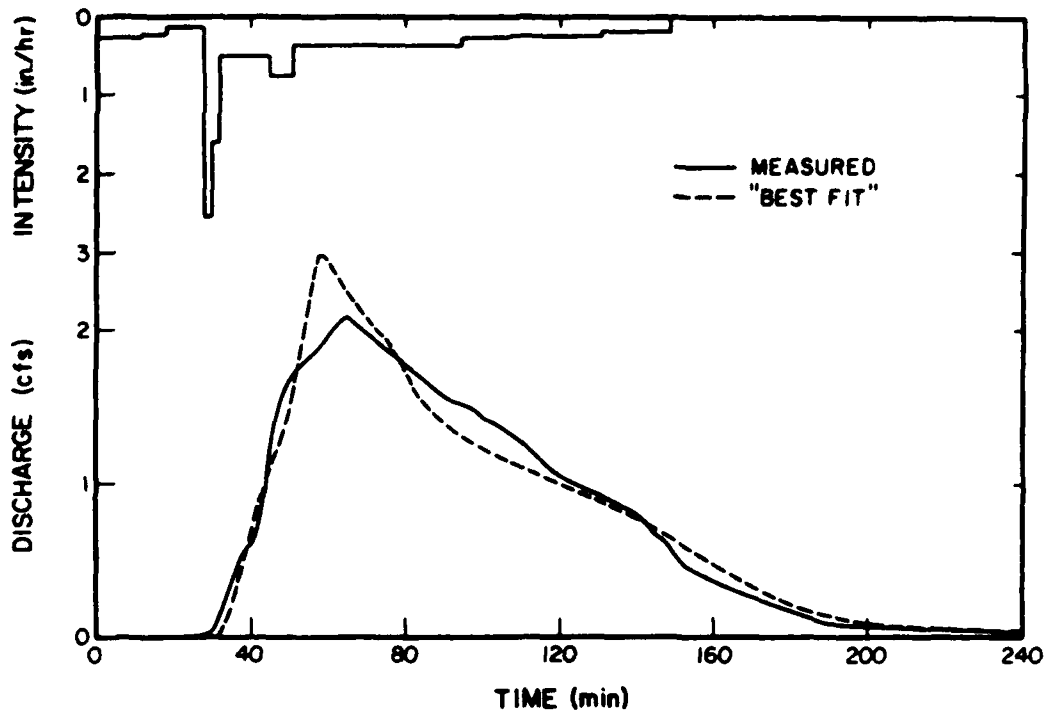

Figure C16. Measured vs. simulated hydrographs for storm event of May 27, 1978 on ISU-2 (note: measured sediment yield = 1270 lb).

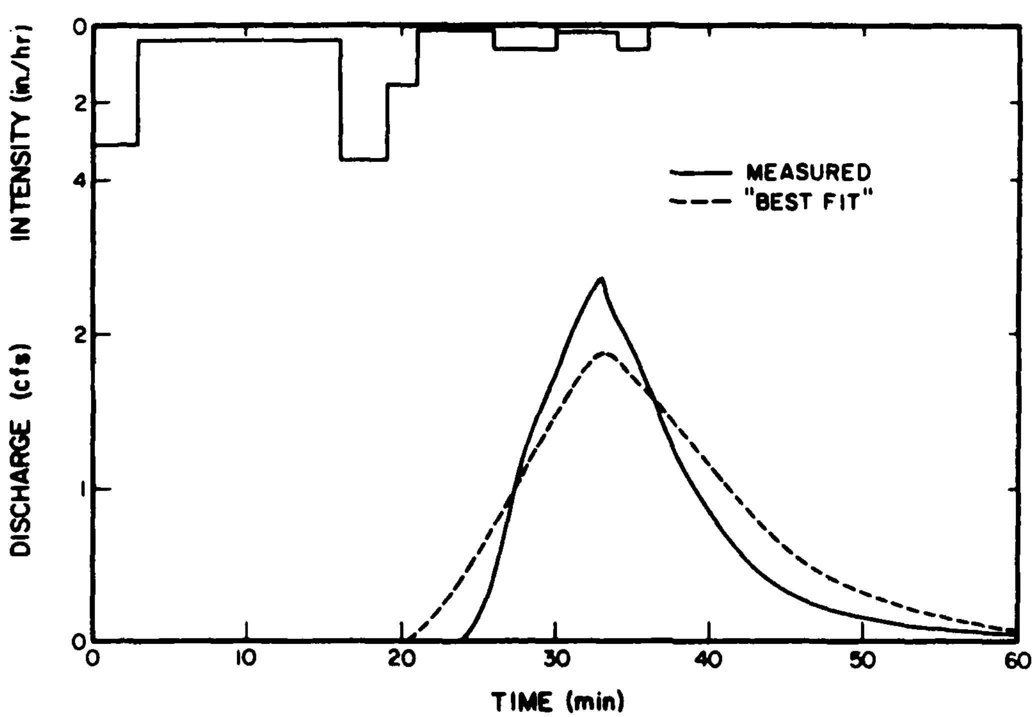

Figure C17. Measured vs. simulated hydrographs for storm event of May 31, 1978 on ISU-2 (note: measured sediment yield = 1940 lb).

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